How to analyze gear failures

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How to analyze gear failures

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By following a step-by-step procedure, engineers can diagnose gear failures and develop solutions. Here's how to conduct a failure analysis, what to look for, and how to recognize common failures.

When an important gear failure occurs, someone becomes responsible for analyzing the failure, determining its cause, and recommending a solution. A company can select its own engineer, an outside consultant, or both. If a consultant is called in, this should be done as early in the process as possible.

Though similar procedures apply to any failure analysis, the specific approach can vary depending on when and where the inspection is made, the nature of the failure, and time constraints.

When and where. Ideally, the engineer conducting the analysis should inspect the failed components as soon after failure as possible. If an early inspection is not possible, someone at the site must preserve the evidence based on instructions from the analyst.

If a suitable facility for disassembling and inspecting the gearbox is not available on-site, it may be necessary to find an alternate location or bring the necessary equipment to the site.

Nature of failure. The failure conditions can determine when and how to conduct an analysis. For example, if the gears are damaged but still able to function, the company may decide to continue their operation and monitor the rate at which damage progresses. In this case, samples of the lubricant should be collected for analysis, the reservoir drained and flushed, and the lubricant replaced.

If gearbox reliability is crucial to the application, the gears should be examined by magnetic particle inspection to ensure that they have no cracks. The monitoring phase will consist of periodically checking the gears for damage by visual inspection and by measuring sound and vibration.

Time constraints. In some situations, the high cost of shutting down equipment limits the time available for inspection. Such cases call for careful planning. For example, dividing tasks between two or more analysts reduces the time required.

Preparing for inspection

Before visiting the failure site, interview a contact person located at the site and explain what you need to inspect the gearbox including personnel, equipment, and working conditions.

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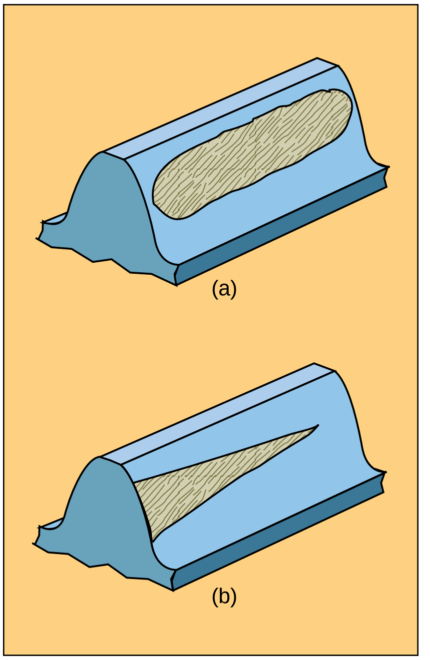

Figure 1 — Typical gear tooth contact patterns: (a), aligned, and (b), misaligned.

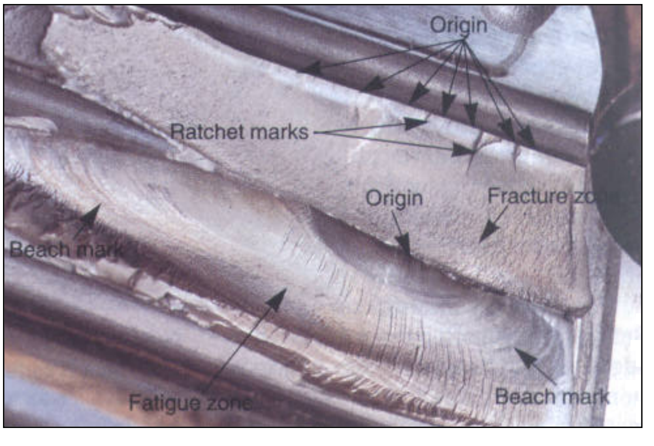

Figure 2 — Bending fatigue fracture surfaces of gear teeth. Upper tooth has multiple origins of failure.

PRODUCT FOCUS: GEARING

Request a skilled technician to disassemble the equipment under your direction. But, make sure that *no work is done on the gearbox until you arrive.* This means no disassembly or cleaning. Otherwise, a well-meaning technician could inadvertently destroy evidence.

Verify that the gearbox drawings, disassembly tools, and adequate inspection facilities are available.

Ask for as much background information as possible, including manufacturer's part numbers, gear and bearing runtime (hr), service history, and lubricant type.

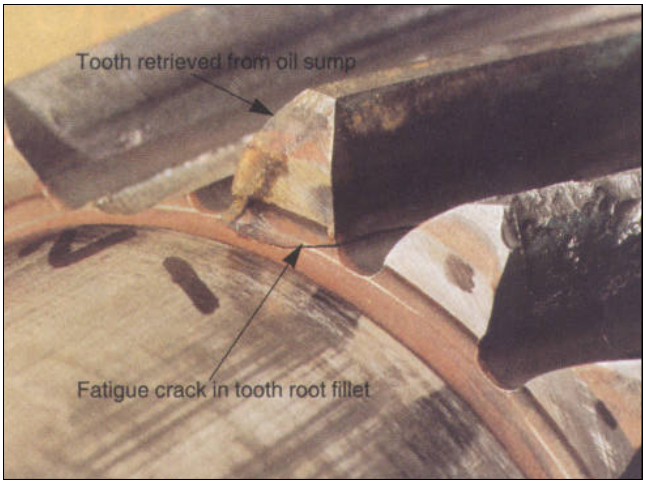

Figure 3 — Fatigue crack in a gear tooth root fillet.

Now, it's time to assemble your inspection equipment, including items such as a magnifying glass, measuring tools, felt tip markers, lubricant sampling equipment, and photographic equipment. A well-designed set of inspection forms for the gearbox, gears, and bearings should be at the top of your priority list.

Failure inspection

Before starting the inspection, review the background information and service history with the contact person. Then interview those involved in the design, installation, operation, maintenance, and failure of the gearbox. Encourage them to tell everything they know about the gearbox even if they feel it is not important.

After completing the interviews, explain your objectives to the technician who will be working with you. Review the gearbox assembly drawings with the technician, checking for potential disassembly problems.

Visual examination. Before disassembling the gearbox, thoroughly inspect its exterior. Use an inspection form as a guide to ensure that you record important data that would otherwise be lost once disassembly begins. For example, the condition of seals and keyways must be recorded before disassembly. Otherwise, it will be impossible to determine when any damage may have occurred to these parts. Gear tooth contact patterns should be taken before completely disassembling the gearbox (see next section).

After the external examination, disassemble the gearbox and inspect all internal components, both failed and undamaged. Examine closely the functional surfaces of gear teeth and bearings and record their condition. Before cleaning the parts, look for signs of corrosion, contamination, and overheating.

After the initial inspection, wash the components with solvents and re-examine them. This examination should be as thorough as possible because *it is often the most important phase of the investigation* and may yield valuable clues. A low power magnifying glass and pocket microscope are helpful tools for this examination.

It is important to inspect the bearings because they often provide clues as to the cause of gear failure. For example:

- Bearing wear can cause excessive radial clearance or end play that misaligns the gears.
- Bearing damage may indicate corrosion, contamination, electrical discharge, or lack of lubrication.
- Plastic deformation between rollers and raceways may indicate overloads.
- Gear failure often follows bearing failure.

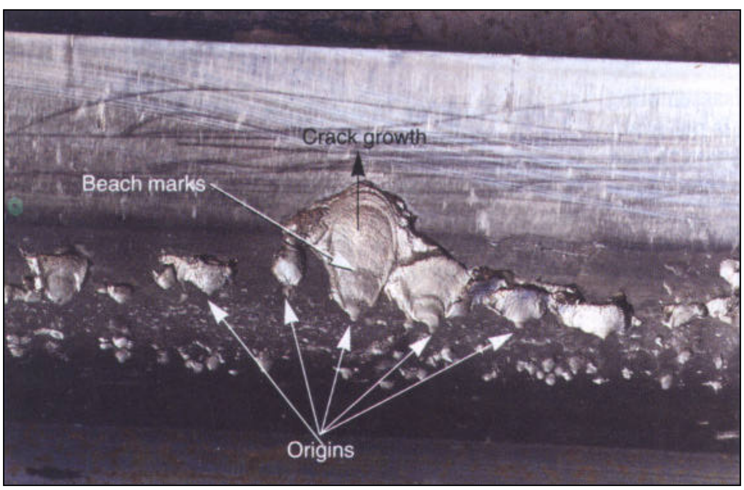

Figure 4 — Fatigue failure (pitting) in the contact surface of a gear tooth. Beach marks are visible in some of the larger pits.

Gear tooth contact patterns. (Complete this step before disassembling gearbox components for inspection). The way in which mating gear teeth contact indicates how well they are aligned, Figure 1. If practical, record tooth contact patterns under either loaded or unloaded conditions. For no-load tests, paint the teeth of one gear with marking compound. Then, roll the teeth through mesh so the compound transfers the contact pattern to the unpainted gear. Lift the pattern from the gear with scotch tape and mount it on paper to form a permanent record.

For loaded tests, paint several teeth on

Table 1 — Gear tooth failure nomenclature

Class	General mode	Specific mode
Bending fatigue	Low-cycle fatigue High-cycle fatigue	Root fillet cracks Profile cracks Tooth end cracks
Contact fatigue	Macropitting	Nonprogressive Progressive Spall Flake
	Micropitting Subcase fatigue	
Wear	Adhesion	Mild Moderate
	Abrasion	Mild Moderate Severe
	Corrosion Fretting corrosion	
	Polishing	Mild Moderate Severe
	Electric discharge Cavitation Erosion	
Scuffing	Scuffing	Mild Moderate Severe
Overload	Brittle fracture Ductile fracture Mixed-mode fracture	
	Plastic deformation	Cold flow Hot flow Indentation Rolling Rippling Ridging Root fillet yielding Tip-root interference
Cracking	Hardening cracks Grinding cracks Rim and web cracks Case-core separation	

one or both gears with machinist's layout lacquer. Run the gears under load for a sufficient time to wear off the lacquer and establish the contact patterns. Photograph the patterns to obtain a permanent record.

Document observations. Describe all important observations in writing, using sketches and photographs where needed. Identify and mark each component (including gear teeth and bearing rollers), so it is clearly identified in the written description, sketches, and photographs. It is especially important to mark all bearings, including inboard and outboard sides, so their location and position in the gearbox can be determined later.

Describe components in a consistent way. For example, always start with the same part of a bearing and progress through the parts in the same sequence. This helps to avoid overlooking any evidence.

Concentrate on collecting evidence, not on determining the cause of failure. Regardless of how obvious the cause may appear, do not form conclusions until all the evidence is considered.

Gear geometry. The load capacity of the gearset will need to be calculated later. For this purpose, obtain the following geometry data, either from the gears and gear housing or their drawings:

- Number of teeth.
- Outside diameter.
- Face width.
- Gear housing center distance for each gearset.
- Whole depth of teeth.
- Tooth thickness (both span and top land measurement).

Specimens for laboratory tests. During the inspection, you will begin to formulate hypotheses regarding the cause of failure. With these hypotheses in mind, select specimens for laboratory testing. Take broken parts for laboratory evaluation or, if this is not possible, ensure that they will be preserved for later analysis.

Oil samples can be very helpful. But, an effective lubricant analysis depends on how well the sample represents the operating lubricant. To take samples from a gearbox drain valve, first discard stagnant oil from the valve. Then take a sample at the start, middle, and end of a drain to avoid stratification. To sample from the reservoir, draw samples from the top, middle, and near the bottom. Examine the oil filter and magnetic plug for wear debris and contaminants.

Samples from the oil storage drum or reservoir can uncover problems such as excessive water in the oil due to improper storage.

Have you got it all? Before leaving the site, make sure that you have everything needed — completed inspection forms, written descriptions and sketches, photos, and test specimens — for completing the failure analysis.

Determine type of failure

Now it's time to examine all of the information and determine how the gear (or gears) failed.

Several failure modes may be present and you need to identify which is the primary mode, and which are secondary modes that may have contributed to failure. Table 1 lists six general classes of gear failure modes, of which the first four are the most common. An understanding of these four common modes will enable you to identify the cause of failure.

1. Bending fatigue. This common type of failure is a slow, progressive failure caused by repeated loading. It occurs in three stages:

- Crack initiation. Plastic deformation

occurs in areas of stress concentration or discontinuities, such as notches or inclusions, leading to microscopic cracks.

- Crack propagation. A smooth crack grows perpendicular to the maximum tensile stress.
- Fracture. When the crack grows large enough, it causes sudden fracture.

As a fatigue crack propagates, it leaves a series of "beach marks" — visible to the naked eye — that correspond to positions where the crack stopped, Figure 2. The origin of the crack is usually surrounded by several concentric curved beach marks.

Most gear tooth fatigue failures occur in the tooth root fillet, Figure 3, where cyclic stress is less than the yield strength of the material and the number of cycles is more than 10,000. This condition is called high-cycle fatigue. A large part of the fatigue life is spent initiating cracks, whereas a shorter time is required for the cracks to propagate.

Stress concentrations in the fillet often cause multiple crack origins, each producing separate cracks. In such cases, cracks propagate on different planes and may join to form a step, called a ratchet mark, Figure 2.

2. Contact fatigue. In another failure mode, called contact or Hertzian fatigue, repeated stresses cause surface cracks and detachment of metal fragments from the tooth contact surface, Figure 4. The most common types of surface fatigue are macropitting (visible to the naked eye) and micropitting.

Macropitting occurs when fatigue cracks start either at or below the surface. As the cracks grow, they cause a piece of surface material to break out, forming a pit with sharp edges.

Based on the type of damage, macropitting is categorized as nonprogressive, progressive, spall, or flake. The nonprogressive type consists of pits less than 1 mm diam in localized areas. These pits distribute load more evenly by removing high points on the surface, after which pitting stops.

Progressive macropitting consists of pits larger than 1 mm diam that cover a significant portion of the tooth surface.

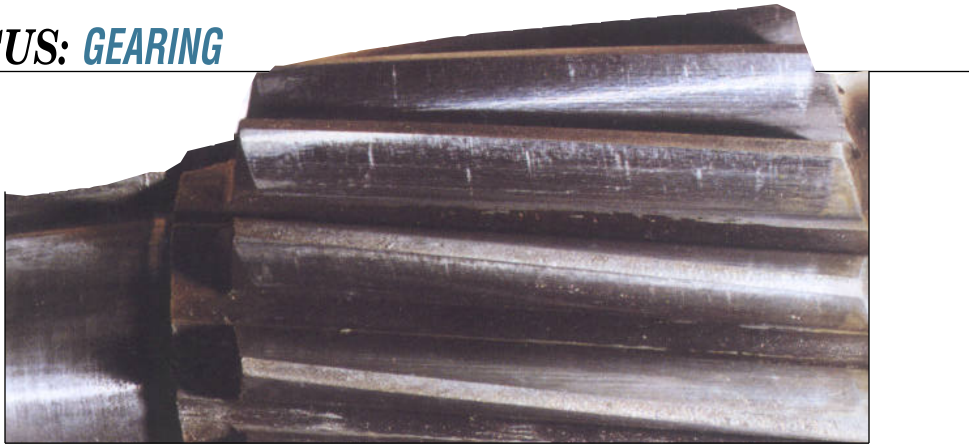

Figure 5 — Adhesion type wear of gear teeth.

In one type, called spalling, the pits coalesce and form irregular craters over a large area.

In flake macropitting, thin flakes of material break out and form triangular pits that are relatively shallow, but large in area.

Micropitting has a frosted, matte, or gray stained appearance. Under magnification, the surface is shown to be covered by very fine pits (less than 20 μm deep). Metallurgical sections through these pits show fatigue cracks that may extend deeper than the pits.

3. Wear. Gear tooth surface wear involves removal or displacement of material due to mechanical, chemical, or electrical action. The three major types of wear are adhesion, abrasion, and polishing.

Adhesion is the transfer of material from the surface of one tooth to that of another due to welding and tearing, Figure 5. It is confined to oxide layers on the tooth surface. Adhesion is categorized as mild or moderate, whereas severe adhesion is termed scuffing (described later).

Typically, mild adhesion occurs during gearset run-in and subsides after it wears local imperfections from the surface. To the unaided eye, the surface appears undamaged and machining marks are still visible. Moderate adhesion removes some or all of the machining marks from the contact surface. Under certain conditions, it can lead to excessive wear.

Abrasion is caused by contaminants in the lubricant such as sand, scale, rust, machining chips, grinding dust, weld splatter, and wear debris. It appears as smooth, parallel scratches or gouges, Figure 6.

Abrasion ranges from mild to severe. Mild abrasion consists of fine scratches that don't remove a significant amount of material from the tooth contact surface, whereas moderate abrasion removes most of the machining marks.

Severe abrasion, which removes all machining marks, can cause wear steps at the ends of the contact surface and in the dedendum. Tooth thickness may be reduced significantly, and in some cases, the tooth tip is

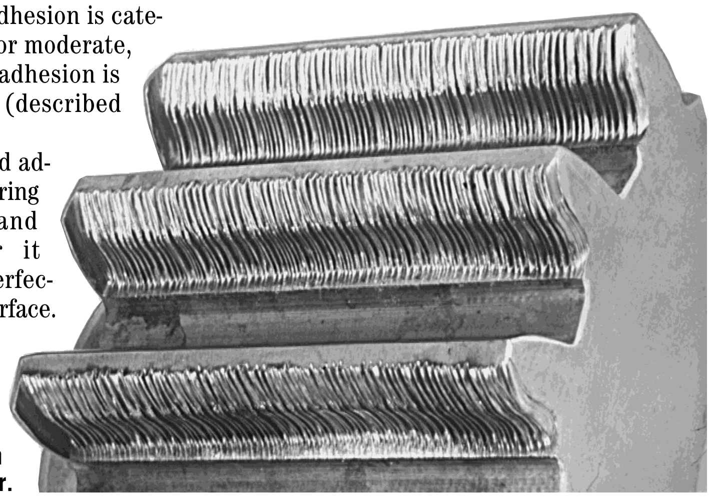

Figure 6 — Excessive abrasion type wear.

Photo: ANSI/AGMA Standard 110.04

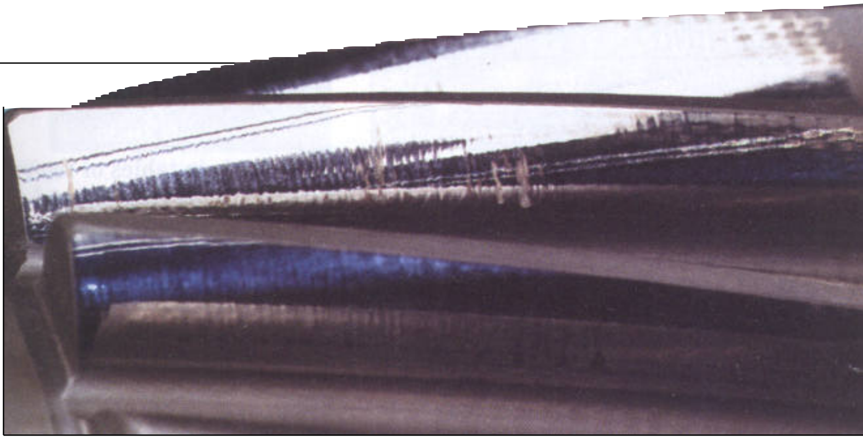

Figure 7 — Polishing type wear.

reduced to a sharp edge.

Finally, polishing is fine-scale abrasion that imparts a mirror-like finish to gear teeth, Figure 7. Magnification shows the surface to be covered by fine scratches in the direction of sliding. Polishing is promoted by chemically active lubricants that are contaminated with a fine abrasive.

Polishing ranges from mild to severe. Its mild form, which is confined to high points on the surface, typically occurs during run-in and ceases before machining marks are removed. Moderate polishing removes most of the machining marks.

Severe polishing removes all machining marks from the tooth contact surface. The surface may be wavy or it may have wear steps at the ends of the contact area and in the dedendum.

4. Scuffing. Severe adhesion or scuffing transfers metal from the surface of one tooth to that of another, Figure 8. Typically, it occurs in the addendum or dedendum in bands along the direction of sliding, though load concentrations can cause localized scuffing. Surfaces have a rough or matte texture that, under magnification, appear to be torn and plastically deformed.

Scuffing ranges from mild to severe. Mild scuffing occurs on small areas of a tooth and is confined to surface peaks. Generally, it is nonprogressive.

Moderate scuffing occurs in patches that cover significant portions of the teeth. If operating conditions do not change, it can be progressive.

Severe scuffing occurs on significant portions of a gear tooth (for example, the entire addendum or dedendum). In some cases, surface material is plastically deformed and displaced over the tooth tip or into the tooth root. Unless corrected, it is usually progressive.

Tests and calculations aid analysis

In many cases, failed parts and inspection data don't yield enough information to determine the cause of failure. When this happens, gear design calculations and laboratory tests are usually needed to develop and confirm a hypothesis for the probable cause.

Gear design calculations. The gear geometry data collected earlier aids in estimating tooth contact stress, bending stress, lubricant film thickness, and gear tooth contact temperature based on transmitted loads for each gear. These values are calculated according to American Gear Manufacturers Association standards such as ANSI/AGMA 2001-B88 for spur and helical gears. Comparing these calculated values with AGMA allowable values helps to determine the risk of macropitting, bending fatigue, and scuffing.

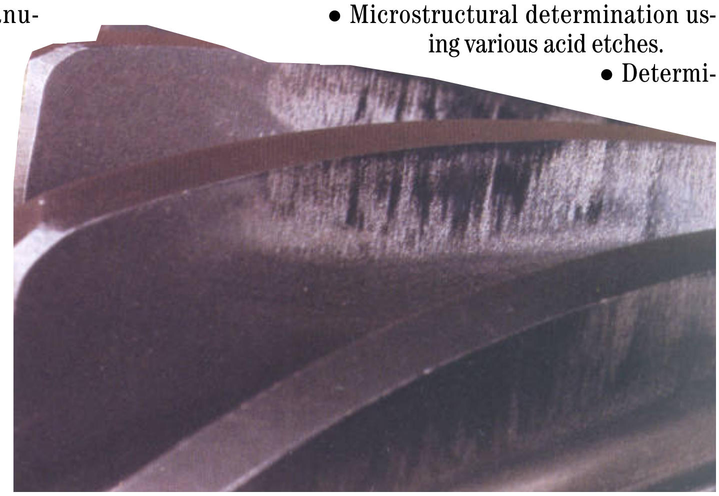

Figure 8 — Scuffing of gear tooth surfaces.

Laboratory examination and tests. A microscopic examination may confirm the failure mode or find the origin of a fatigue crack. Both light microscopes and scanning electron microscopes (SEM) are useful for this purpose. An SEM with an energy dispersive X-ray is especially useful for identifying corrosion, contamination, or inclusions.

If the primary failure mode is likely to be influenced by gear geometry, check for any geometric or metallurgical defects that may have contributed to the failure. For example, if tooth contact patterns indicate misalignment or interference, inspect the gear for accuracy on gear inspection machines. Conversely, where contact patterns indicate good alignment and the calculated loads are within rated gear capacity, check the teeth for metallurgical defects.

Conduct nondestructive tests before any destructive tests. These nondestructive tests, which aid in detecting material or manufacturing defects and provide rating information, include:

- Surface hardness and roughness.
- Magnetic particle inspection.
- Acid etch inspection.
- Gear tooth accuracy inspection.

Then conduct destructive tests to evaluate material and heat treatment. These tests include:

- Microhardness survey.
- Microstructural determination using various acid etches.
- Determi-

nation of grain size.

- Determination of nonmetallic inclusions.
- SEM microscopy to study fracture surfaces.

Form and test conclusions

When all calculations and tests are completed, you need to form one or more hypotheses for the probable cause of failure, then determine if the evidence supports or disproves the hypotheses. Here, you need to evaluate all of the evidence that was gathered including:

- Documentary evidence and service history.
- Statements from witnesses.
- Written descriptions, sketches, and photos.
- Gear geometry and contact patterns.
- Gear design calculations.
- Laboratory data for materials and lubricant.

Results of this evaluation may make it necessary to modify or abandon the initial hypotheses. Or, pursue new lines of investigation.

Finally, after thoroughly testing the hypotheses against the evidence, you reach a conclusion about the most probable cause of failure. In addition, you may identify secondary factors that contributed to the failure.

Reporting results

A failure analysis report should describe all relevant facts found during the analysis, the inspections and tests, weighing of evidence, conclusions, and recommendations. Present the data succinctly, preferably in tables or figures. Good photos are especially helpful for portraying failure characteristics.

The report usually contains recommendations for repairing the equipment, or making changes in equipment design or operation to prevent future failures. ■