Static, dynamic and fatigue analysis of a semi-automatic gun locking block

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\textbf{A B S T R A C T}

Reduction of the recoil forces on shotgun parts and even effects on the human body are a considerable importance during design of the semi-automatic shotgun parts. These forces are strongly affected by the dynamics of motion of rifle parts upon firing. Therefore, managing of these recoil forces would be crucial issue to produce functional, ergonomic, safe, reliable, and robust designs. In the literature, many researchers have investigated static, dynamic, and fatigue behaviors of most mechanical parts which especially take a role under the dynamic loads. However, shotgun parts have not been investigated formally yet. Therefore, in this study we particularly focused on investigating static, dynamic, and fatigue behaviors of a semi-automatic shotgun’s locking block, which is an integral part of the shotgun mechanism during firing. In this study, techniques such as hardness measurements, analysis of the recoil forces of a semi-automatic shotgun, and finite element analysis were performed. Pro/Engineer Wildfire 3.0 series software was used to model the locking block and the other parts of the gun. Moreover, the finite element code ANSYS/LS-DYNA, and ANSYS Workbench were used to determine the stress distribution, and fatigue behaviors of the locking block, based on the Morrow Theorem.

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1. Introduction

The Gun industry has been increasing its production capacity in the last decades and many kinds of semi-automatic shotgun have been manufactured by the gun industry. Considering this point, we can understand how the responsibility of producing more functional, ergonomic, safe, reliable, and robust designs has become a crucial issue in the recent years. Many studies have been carried out on different dynamic component of failure analysis. However, there is not enough study carried out to investigate the failure mode of shotgun components. Yu et al. [1] examined the failure analysis of the M16 rifle bolt. Their study showed that the fracture had occurred because of the high stress concentrations at the fillet radius of the bolt.

Principally, recoil-operated autoloaders use the force naturally generated by recoil from the firing process to eject the spent cartridge, get a new one from the magazine and ready it in the chamber. In this case, the explosion from the cartridge forces the dynamic components (bolt, action bar, and locking block), which had been positioned inside of the rifle body continue to move backward under their own momentum after explosion. At this time, the action bar pushes the hammer backwards and the trigger group becomes ready for the next shot. Immediately after, the back face of the bolt strikes against the plastic stroke absorber (Fig. 2) that had been attached to the main body of the shotgun to decrease the instantaneous shock...
forces after crashing. However, the action bar keeps moving and hits strongly over the lugs of the locking block (Fig. 2). Even though, these loads would have negligible effects while using the lower pressured cartridges in the shotgun, on the other hand, high pressured cartridges associates with the higher recoil speeds and recoil forces. Therefore, these kinds of high dynamic forces would cause considerably high damages on the locking block. Particularly, if shotgun does not contain any kind of over-pressure unloading system (gas-discharge system) as it was subjected as a sample in our study. In this paper, the locking block of semi-automatic shotgun, which does not include gas-discharging system was investigated as a sample. Loading and crashing position of this shotgun mechanism can be seen from Figs. 1 and 2. Additionally, Fig. 3 indicates the technical drawing of the locking block.

2. Chemical composition and hardness measurements

The locking block was analyzed from a metallurgical viewpoint. This analysis determined whether additional factors other than stress concentrations contributed to the locking block failure. The fractured locking block was made of AISI 4340 wrought material. The chemical composition of material can be seen in Table 1. As it can be seen from this table the specimen’s material composition is in balance with the specific properties of the material. AISI 4340 steel constitutes a very important engineering material employed in the manufacture of many different parts and components which include automotive crankshafts and rear axle shafts, high pressure equipments (pressure vessels and reactors), crankshafts, connect-

Fig. 1. Firing position state of shotgun mechanism.

Fig. 2. Crashing and loading position state and of shotgun mechanism.

Fig. 3. Technical drawing of the analyzed locking block. Dimensions are in mm.
ing rods, propeller hubs, gears, drive shafts, shotgun piston slides, power transmission gears, landing gear parts, and heavy-duty parts of rock drills [2–5]. Additionally, AISI 4340 steel is widely used in the aircraft industry for fabrication of structural components, in which strength and toughness are important design requirements. It is heat treatable, low alloy steel containing nickel, chromium, and molybdenum. It features good performance when under cyclic loads, retaining good fatigue strength while developing high tensile strength in heat treated condition [6,7].

Hardness measurements were carried out on a cross-sectional area at the fillet points which are 0.1, 0.5, 1, 2, 3, 4, 5, and 6 mm away from the locking lugs of the locking block, using a Vickers microhardness tester under a load of 500 g. The hardness values are illustrated in Fig. 4. As displayed on this graph, hardness values near the fracture region and 6 mm away from this fracture line are of approximately the same hardness level. On the other hand, plastic deformations near the locking lugs and rear edges have increased the hardness level in these damaged regions.

3. Analysis of the recoil forces acting on a shotgun mechanism

A series of experimental studies was performed on the shooting range using a 12 – 3 in. semi-automatic slugged barrel rifle (barrel length = 700 mm, without shock in the barrel). In these tests, force and speed sensors were used to determine the average muzzle-velocity of the shotgun, average recoil force and recoil speed of the action bar, using different brands cartridges with the same technical properties (such as Remington, Fiocchi, Winchester, and Bornaghi). The maximum average recoil force and speed (780 N, 16 m/s) of action bar, which strikes against the locking block after firing, and muzzle velocity of bullet (422 m/s) were obtained using the 12 – 3” Remington Slugger Rifled shotgun cartridge (12 – gauges, 3 in. – shell length, and 28 g – bullet mass). Consequently, these results were used in the “FEA” analysis.

Average force \( F_a \) acting on the bullet during its motion was calculated based on some assumptions using Newton’s second law:

\[
F_a = \frac{0.028 \text{kg} \times 422 \frac{\text{m}}{\text{s}}}{0.0015 \text{s}} = 7877.3 \text{ N}
\]

- \( 0.028 \text{kg} \) Mass of the bullet
- \( 422 \frac{\text{m}}{\text{s}} \) Bullet muzzle velocity
- \( 0.0015 \text{s} \) Bullets leaving time from the gun muzzle

According to this equation, if the gun had been rigidly attached to the ground this actual force (7877.3 N) would be the effective recoil force applied to the support. This simple calculation indicates that how big forces strike the rifle parts and why reduction of recoil forces acting on the human body and on the shotgun parts is such an important issue.

However, some factors cause the recoil force acting on a human body to be much smaller than 7877.3 N, such as the mass of the rifle is approximately 100 times larger than the mass of the bullet, which is travelling in the opposite direction after firing. Additionally, only a small amount of the explosion energy ends up as a dynamic recoil force. Finally, motion of the locking block, bolt, and bolt carrier (action bar) as well as friction between all moving parts also influence the resultant recoil force.

### Table 1

Chemical composition (wt%) of the locking block.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Ni</th>
<th>Cr</th>
<th>Mn</th>
<th>Mo</th>
<th>Si</th>
<th>S</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analyzed</td>
<td>0.412</td>
<td>1.893</td>
<td>0.863</td>
<td>0.732</td>
<td>0.241</td>
<td>0.325</td>
<td>0.02</td>
<td>Balance</td>
</tr>
<tr>
<td>As specified [5]</td>
<td>0.41</td>
<td>1.88</td>
<td>0.87</td>
<td>0.76</td>
<td>0.27</td>
<td>0.33</td>
<td>0.022</td>
<td>Balance</td>
</tr>
</tbody>
</table>

![Fig. 4. Vickers microhardness test graph under a load of 500 g.](image-url)
4. CAD and finite element modeling

Three-dimensional (3-D) finite element analysis (FEM) has been widely used for the quantitative evaluation of stress in the critical zones of a structure. Therefore, in this study FEA was selected to examine the effects of the static and dynamic loads on a shotgun locking block. Additionally, a well-known solid modeling software, Pro/Engineer Wildfire-3.0, was used to design the first basic parts of the semi-automatic shotgun (Fig. 5). Afterwards, these parts were imported to ANSYS/LS-DYNA in the ACIS format. Finally, the software was used to design a gas-discharge system, and to modify the locking block, taking the FEA stress analysis and failure analysis outcomes into consideration.

4.1. Dynamic crash analysis of the semi-automatic shotgun mechanism using ANSYS/LS-DYNA

ANSYS/LS-DYNA can be efficiently used in dynamic analysis a number of models in most areas in engineering. A study of stress distribution in the locking block subject to the repeated load was conducted with ANSYS/LS-DYNA as an explicit dynamic analysis to determine the instantaneous stress waves on the locking block after crashing. Standard piecewise linear material behavior was assigned to the locking block and action bar was specified as a rigid material. Fig. 6 shows explicit dynamic curve of locking block for the AISI 4340 wrought material.

The FEM model consisted of total 12,911 eight-node orthotropic elements; 10,340 elements for the locking block and 2571 elements for the action bar. SOLID164 type element which is only used in explicit dynamic analyses was determined for both parts and each node has three degree of freedom (DOF). Material properties of the locking block were accepted: Young’s modulus $E = 205$ GPa, Poisson’s ratio $\nu = 0.29$, density $\rho = 7850$ kg/m$^3$, yield strength $\sigma_y = 1100$ MPa, ultimate tensile strength $\sigma_u = 1468$ MPa. Action bar was modeled as a rigid material with Young’s modulus $E = 205$ GPa, Poisson’s ratio $\nu = 0.3$, density $\rho = 7850$ kg/m$^3$. A constrain set had been created from the back rounds surface of the locking block and the recoil speed of the action was accepted as $v = 16$ m/s. The dynamic crash analysis was conducted using an explicit solution method (Fig. 7).

Fig. 5. Model of shotgun locking block and action bar generated in Proengineer.

Fig. 6. Explicit dynamic curve for the AISI 4340 steel.
In this analysis, the action bar has a degree of independence in the direction “Z”. Automatic node to surface contact algorithm was determined between the action bar and the locking block, and contact stiffness was accepted as 0.1.

When the action bar crashed into the locking block at a speed of 16 m/s, the instantaneous peak stress (SMX), was within 0.1 s obtained as 1290 MPa, which is above the material yield stress value ($\sigma_y = 1100$ MPa). Fig. 8 indicates the Von-Mises stress distribution on the investigated part. The dynamic analysis shows that high stress concentrations were found at the front radiused surfaces and sharp filled edges of the locking block, which compare well with the crack initiation and crack propagation direction on the failed locking block surfaces (Figs. 9 and 10). Consequently, we conclude that the locking
block of the shotgun part had been exposed to a high dynamic load and this analyze revealed that this over loading caused the plastic deformation on the critical zones. As a result of these higher stresses, material failures even with low-cycle loadings become an unavoidable issue. Moving from this point, a strain based fatigue analysis was carried out in the next study to ensure the safety of the design, the failure life of the product with the different loading values and, additionally, to determine the damage distribution in the critical zones, and finally, to ensure the fatigue behaviors of the locking block under the static loading conditions.

4.2. Fatigue analysis of the locking block using ANSYS Workbench

“LCF” failures typically result from flaws in the material (impurities or voids), poor or inconsistent manufacturing processes, complex geometries (bolt holes, scallops, blade slots, etc.) that create high stress regions (hot spots) on the component, and wear between components. However, even “perfect” components have a finite life. They fatigue in operational heat and stress environments, and after a certain number of cycles they fail [8].

In this study, the fatigue life of the locking block upon finite element “Low Cycle Fatigue” (LCF) strain analysis was predicted based on Morrow’s equation. Based on the proposal by Morrow (1965), the relation of the total strain amplitude ($\varepsilon_a$) and the fatigue life in the reversals to failure ($2N_f$) can be expressed in the following equation:

$$
\varepsilon_a = \frac{\sigma_f}{E} \left( 1 - \frac{\sigma_m}{\sigma_f} \right) (N_f)^b + \varepsilon'_f (2N_f)^c \quad [9]
$$

The material and strain life properties of the locking block used in this fatigue analysis are listed in Table 2. Fig. 11 indicates the strain life curve of AISI 4340 wrought material. Von-Mises stresses obtained from finite element analysis were utilized in fatigue life calculations. Fatigue analysis had been performed according to infinite life criteria ($N = 1e^7$ cycle) and safety of the design was assumed as 10,000 loading cycles. Applied maximum average recoil force on the edge of locking block (Fig. 12) which had been determined from the test result is 780 N. Additionally, the fatigue strength factor ($K_f$) was accepted as 1. Upper and lower variations of the applied force were accepted as 1% and 100% of the actual force. Zero-based (apply a load then remove it) constant amplitude loading condition was assigned to the locking block.

### Table 2

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>205 GPa</td>
</tr>
<tr>
<td>Density</td>
<td>7850 kg/m³</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.29</td>
</tr>
<tr>
<td>Yield strength</td>
<td>1100 MPa</td>
</tr>
<tr>
<td>Ultimate tensile strength</td>
<td>1468 MPa</td>
</tr>
<tr>
<td>Strength coefficient</td>
<td>1879 MPa</td>
</tr>
<tr>
<td>Strength exponent</td>
<td>–0.86</td>
</tr>
<tr>
<td>Ductility coefficient</td>
<td>0.64</td>
</tr>
<tr>
<td>Ductility exponent</td>
<td>–0.636</td>
</tr>
<tr>
<td>Cyclic strength coefficient</td>
<td>1996 MPa</td>
</tr>
<tr>
<td>Cyclic strain hardening exponent</td>
<td>0.135</td>
</tr>
</tbody>
</table>

Fig. 11. Strain life curve for AISI 4340 steel.
The finite element code of ANSYS Workbench was used to obtain the fatigue life, factor of safety and damage distribution on the locking block. The FEM consisted of 14,156 nodes and 8717 elements. 10-Node quadratic tetrahedron SOLID 187 element type was used to create a mesh structure which was selected from the ANSYS element library.

Additionally, mesh refinement had been applied, particularly to the sharp edge and radiuses surfaces (critical zones) (Fig. 13).

The magnitude of the stress experienced on the critical zones of the test sample worked out approximately 890 MPa from the finite element analysis. If we accept that the failure limit of the part as 734 MPa (0.5 \times \text{ultimate tensile strength}), it can be seen that the calculated stress is much bigger than the failure limit of the part. Additionally, this result indicates that the Von-Mises stress distribution in the locking block showed high stress concentrations (because of over loading) present at the sharp edges which are located on the rear side of the locking block and at the radiuses face located on the front face of the part (Fig. 14).

Additionally, these higher stress concentrations contributed to the crack initiation, which can be proved by the picture of the crack growing from the front face (radiuses face) next to the sharp edge (rear face), as shown in Fig. 9.

Fig. 15 represents the available life (the number of cycles in constant loading conditions until the part will fail due to fatigue) for the given fatigue analysis. As it can be seen from this figure, minimum life (2514 cycle) has been determined at the critical zones of the locking block.

Fig. 16 indicates failure life of the locking block according to variation of loading limit (lowest case is 1% of the actual force, highest case is 100% of the actual force). If the minimum limit of the loading variation is 1% of the actual force, fatigue life of the component approaches infinite life. (5.82e^7 cycle). Additionally, Table 3 represents the different failure lives of the locking block in the different loading values.
Fig. 17 indicates fatigue damage which is defined as the design life divided by the available life. As it can be seen in this figure, maximum damage occurs as 3.98 at the critical zones (if the value of this damage is greater than 1, it indicates that the part will fail from fatigue before the design life is reached).

Fig. 18 represents the factor of safety (FS) with respect to a fatigue failure at a given design life. This value depends between the minimum safe zones (0) to maximum safe zones (15). As it can be seen from this figure, minimum safety of the design (0.4217) designates the critical zones.

5. Discussion and conclusions

In this study, static, dynamic, and fatigue behaviors of locking have been investigated. ANSYS/LS-DYNA, which is the most advanced general purpose nonlinear finite element program, explicit dynamic module, was used to predict the instantaneous
stress value and stress distributions on the locking block. The results obtained from this analysis indicate that the locking block has been subjected to high dynamic loads. Consequently, this analysis revealed that overloading has caused the plastic deformation in the critical zones of the part. The fatigue behavior of locking block was also investigated by using another well-known FEA software ANSYS Workbench. The outcomes of this analysis revealed that the locking block fails before reaching the design requirements and the failure process (crack initiation–crack propagation–fracture) starts at the high plastic deformation regions which are in the critical zones.

Table 3
The variation of fatigue life according to applied force.

<table>
<thead>
<tr>
<th>Run</th>
<th>Force (N)</th>
<th>Life minimum (cycle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>780.0 (actual force)</td>
<td>2514.12</td>
</tr>
<tr>
<td>2</td>
<td>300.0</td>
<td>7430.09</td>
</tr>
<tr>
<td>3</td>
<td>100.0</td>
<td>41765.72</td>
</tr>
<tr>
<td>4</td>
<td>30.0</td>
<td>277107.05</td>
</tr>
<tr>
<td>5</td>
<td>15.0</td>
<td>823850.31</td>
</tr>
<tr>
<td>6</td>
<td>1.0 (lowest testing force)</td>
<td>5.82 × 10^7</td>
</tr>
</tbody>
</table>

Fig. 16. Available life diagram of the locking block between the different loading variations (fatigue sensitivity).

Fig. 17. Strain analyze – damaged contours.
Even though, there could be many reasons that the recoil force acting on the shotgun parts are much smaller than it was predicted, it becomes a crucial issue when the shotgun does not contain any kind of gas-discharge (anti-recoil) system. In conclusion, there is nothing wrong with the design of the locking block or the material of this part. Because, a lack of such as this system results over loads on the shotgun parts as it was subjected in our study. The authors strongly recommend the inclusion of a gas-discharge system in gun designs, because it is of considerable importance in decreasing the recoil forces acting on the gun parts and on the human body.

References