Scientific Research and Essays Vol. 5(20), pp. 3134-3140, 18 October, 2010
Available online at http://www.academicjournals.org/SRE
ISSN 1992-2248 ©2010 Academic Journals

Full Length Research Paper

Failure analysis of the semi-automatic shotgun locking block

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Accepted 13 September, 2010

Recently, there have been several occurrences of locking block failure in the semi-automatic shotgun bolts at a shotgun factory in Turkey. The fractured surface and locking block geometry were examined in order to determine failure reasons. The stress distribution of the locking block was performed using ANSYS Workbench 11.0. It was discovered that the reasons for fracture of locking block are: incorrect material selection, incorrect heat treatment, and dimensional geometry problems. For defining best material and heat treatment conditions, AISI 4140 and AISI 4340 steels were used and heat-treated. Tensile, charpy notched-impact and hardness testing were used to fully characterize materials properties. Mechanical test results and fractured surface analysis were analyzed in deciding for proper material. It was concluded that the most convenient material for locking block is AISI 4340 steel and optimum heat treatment parameters for this steel is oil quenching and tempering at 450°C. ANSYS Workbench analysis revealed that overloading has caused plastic deformation in the critical zones of the part.

Key words: Semi-automatic shotgun, locking block, failure analysis, finite element analysis.

INTRODUCTION

The Turkish shotgun industry has been increasing its production capacity in the last decades and many kinds of semi-automatic sport and hunting aimed shotguns have been manufactured. Quality of the shotguns has become important since competition in market demands improved performance and longer service life. There have been occurrences of locking block failure in the semi-automatic shotgun bolts (Figure 1). Locking block is strongly affected by the dynamics of motion of rifle parts upon firing. Therefore, managing of these recoil forces would be crucial to producing functional, ergonomic, safe, reliable and robust designs. One example of the locking block fracture surfaces can be seen in Figure 2.

In the literature, although many studies have been carried out on different component of failure analysis, there is not enough study carried out to investigate the failure mode of shotgun components. Ozmen et al. (2009) examined static, dynamic and fatigue analysis of a semi-automatic gun locking block. Their study showed 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. Yu et al. (2005) examined the failure analysis of the M16 rifle bolt. The study showed that the fracture had occurred due to high stress concentrations at the fillet radius and the additional stress concentration was imposed by the presence of localized pitting at the surface of the bolt.

Investigation on the premature failure of suspension coil spring of a passenger car, which failed within few months after being put into service, has been carried out by Das et al. (2007). According to the results of this study, failure due to typical high cycle fatigue was

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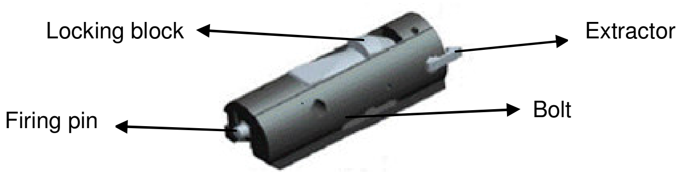

Figure 1. Semi-automatic shotgun bolt.

Figure 2. Fractured locking blocks.

therefore not a possibility. It was also found that the physical dimensions of the spring and grade of steel used are of proven design. The possibility of overloading beyond yield stress was also ruled out after analyzing the record of movement of the automobile. A failure analysis of a tie rod end of a sports utility vehicle (SUV) steering mechanism has been carried out by Falah et al. (2007). Failure analysis results indicate that the primary cause of failure of the tie rod was likely material deficiency.

This paper investigates the leading causes of catastrophic fracture of the bolt under firing conditions. There are three important factors which cause failure of semi-automatic shotgun and parts. These factors are material selection, heat treatment, and dimensional geometry.

MATERIALS AND METHODS

Selection of an engineering material is based upon the design, application and manufacturing feasibility of an object. With that in mind, if the proper material is not used, the specified (and desired) values for each mechanical property (hardness, strength, toughness, etc.) may not be achieved for a given part, regardless of whether heat treatment is performed well or done at all. If the incorrect material is used to make the part, the part may yield a shorter service life, or may even catastrophically fail, resulting in personal injury or death. The same goes when heat treatment of parts is not performed according to design specifications and procedures. If dimensional geometry is incorrect, even a properly heat-treated part made of the correct material, it will either function poorly or it will not last as long as it should (Emerson, 2007).

Selection of suitable materials for firearms applications is very crucial. Alloy steel is major candidate material for shotgun locking block applications due to its superior mechanical properties. Failed semi-automatic shotgun locking blocks are made from AISI 4140. It is also possible to use AISI 4340 alloy steels.

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 equipment (pressure vessels and reactors), crankshafts, connecting rods, propeller hubs, gears, drive shafts, shotgun piston slides, power transmission gears, landing gear parts, and heavy-duty parts of rock drills (Huda, 2005). 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 a 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 (Irvine, 1962). For best material selection AISI 4140 and AISI 4340 alloy steel are compared as locking block material.
The specimens were manufactured out of an AISI 4140 and AISI 4340 alloy steel quenched and tempered. AISI 4140 and AISI 4340 alloy steels were obtained in the form of hot rolled bars having a diameter of 22 mm. Chemical compositions of steels used are given in Table 1.

An understanding of the mechanical properties of metals during deformation over a wide range of loading conditions is of considerable importance for a number of engineering applications. When discussing high strength steel, it is crucial to realize that the definition of so-called high strength depends entirely on how the steel is to be used. These usages tend to fall into a number of different categories where different combinations of properties are required. In each of these categories, researches being carried out to develop higher strength steels have to take the manufacturing processes, heat treatment and the alloying technology into consideration (Huda, 2005).

For the present tests, in order to obtain different quenched-and tempered martensite structures, samples from the received AISI 4140 and AISI 4340 alloy steels are first heated to 680°C for 60 min. This treatment produces similar molecular structure in steel. It is then heated at 860°C for 90 min, followed by oil cooling to produce a quenched martensite structure, and tempered at 150, 250, 275, 315, 350, 450 and 550°C, for 90 min.

Tensile testing was carried out in an Instron tensile testing machine model no. 8801 keeping a constant cross head speed of 3×10^{-3} mm/s. Standard impact specimens (ASTM; Vol 03.01:E23-96) were prepared and Charpy V-notched impact testing was carried out.

The finite element code ANSYS was used to determine the stress distribution in the locking block when subjected to the load and constraints of operational conditions. 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, explosion from the cartridge forces the dynamic components (bolt, action bar, and locking block), which had been positioned inside of the rifle's body to continue to move backward under their own momentum after explosion. At this time, the action bar pushes locking block, setting the hammer backwards and the trigger group becomes ready for the next shot. Additionally, only a small amount of the explosion energy ends up as a dynamic recoil force. Even though, these loads would have negligible effects while using the lower pressured cartridges in the shotgun; on the other hand, high pressured cartridge 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.

In order to analyze the stresses that the block experienced while firing, a three-dimensional model of the block was generated in Solid Works and imported to the ANSYS Workbench 11.0. Subsequently, ANSYS Workbench 11.0 was used to post-process the model in order to calculate the von-Misses stresses in the block. Dimensions and geometry of the locking block are given in Figure 3. Figure 4 displays the three-dimensional model of the locking

Table 1. Chemical compositions of steels.

Steel type	Chemical composition, wt (%)								
AISI	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**Fe**
4140	0.41	0.27	0.94	0.01	0.02	1.01	0.18	0.09	Balance
4340	0.40	0.31	0.73	0.01	0.005	0.83	0.24	1.78	Balance

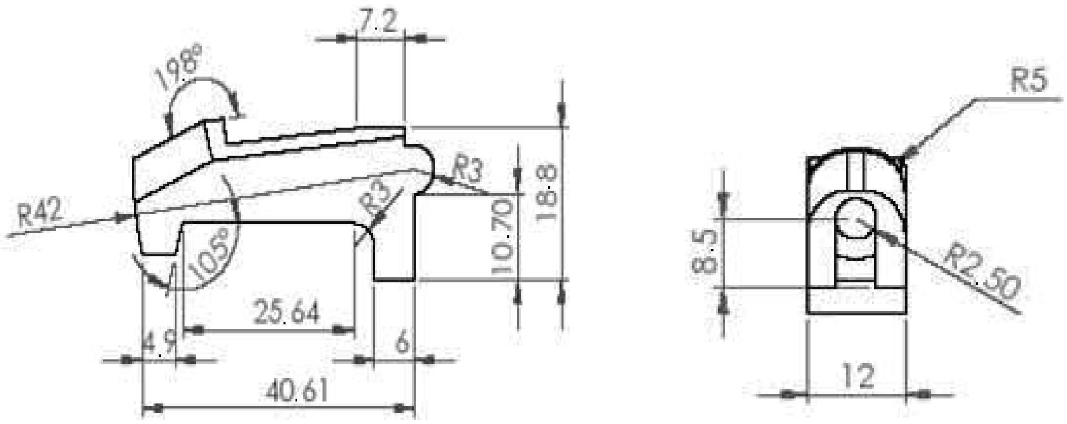

Figure 3. Dimensions and geometry of the bolt (mm).

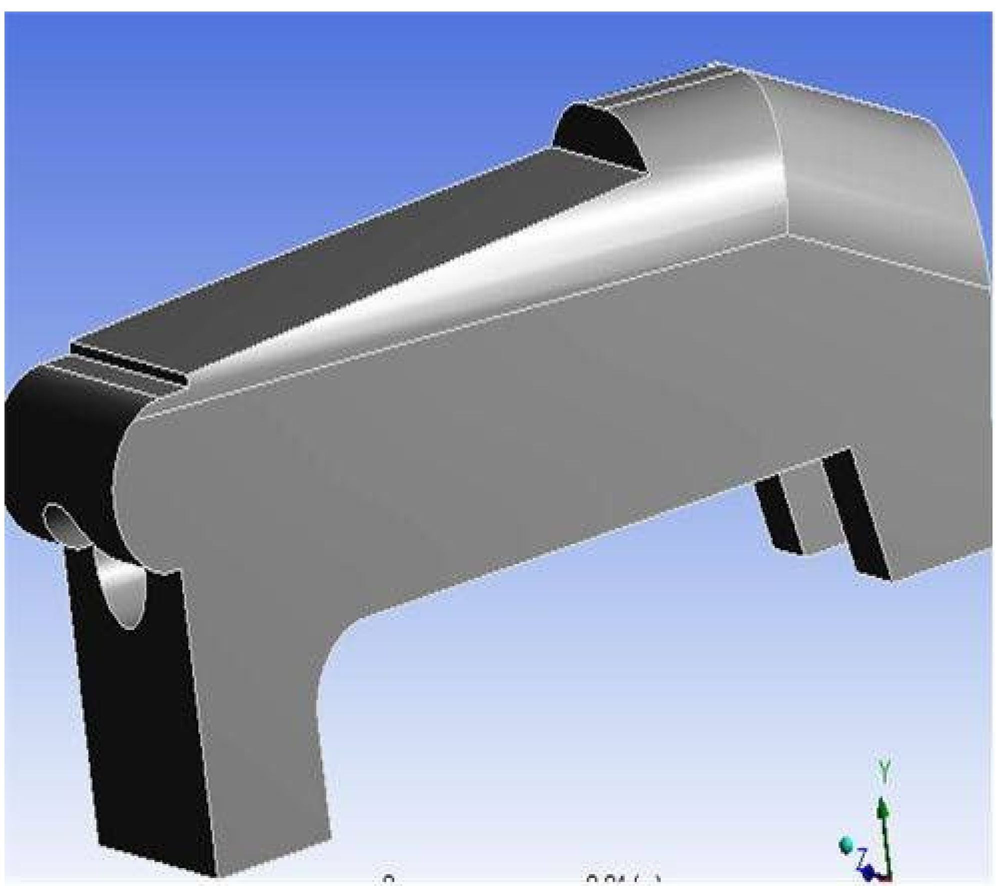

Figure 4. Three-dimensional model of shotgun locking block.

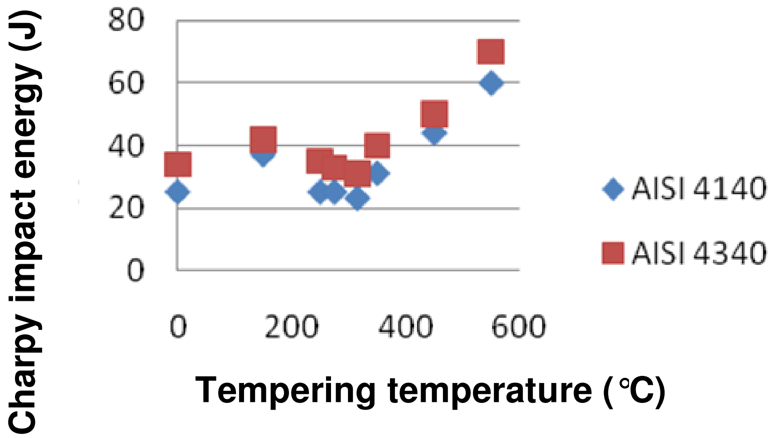

Figure 5. Charpy V-notched impact test results.

Table.2. The mechanical properties of steels after heat treatment.

Tempering temperature (°C)	AISI 4140				AISI 4340			
	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Reduction in area (%)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Reduction in area (%)
Quenching	1910	2102	6	27	2038	2243	7	30
150	1770	1960	7,8	37	1810	2075	8,5	40
250	1680	1875	9,4	39	1750	1930	10,1	43
275	1620	1710	8,4	35	1685	1830	9,5	38
315	1555	1675	8,6	36	1645	1775	9,6	39
350	1420	1540	9,5	40	1510	1625	10,5	43
450	1260	1385	13,2	46	1350	1467	14,1	49
550	1020	1150	15,9	53	1115	1280	17,5	56

Table 3. Hardness test results.

Tempering temperature (°C)		Quenching	150	250	275	315	350	450	550
Brinell hardness	AISI 4140	560	550	487	475	464	451	420	362
	AISI 4340	543	522	470	464	451	442	400	341

block.

RESULTS

Experimental results

After heat treatments, mechanical properties of AISI 440 and AISI 4340 alloy steels are presented in Tables 2, 3 and Figure 5. The mechanical properties, that is, ultimate tensile and yield strengths, reduction in area, elongation, impact toughness and hardness are measured as functions of tempering temperature. For every measurement, two specimens are used, having been quenched (860°C: 90 min) in oil and tempered at 150, 250, 275, 315, 350, 450 and 550°C, for 90 min.

As expected, the mechanical behavior of AISI 4140 and AISI 4340 steels are quite sensitive to the tempering temperature. Under quenched conditions, the materials have the highest level of strength and hardness, but their ductility is the lowest. For the tempering case, the strength and hardness decrease as the tempering temperature is increased. Table 2 shows that tested samples area reduction and elongation varied with the tempering temperature. It is clear that the ductility of material increases with the tempering temperature, but that there is then a drop in toughness and ductility when tempered at 275 and 315°C. It is fairly a general cause of tempered martensite embrittlement.

It has been known for many years that high strength

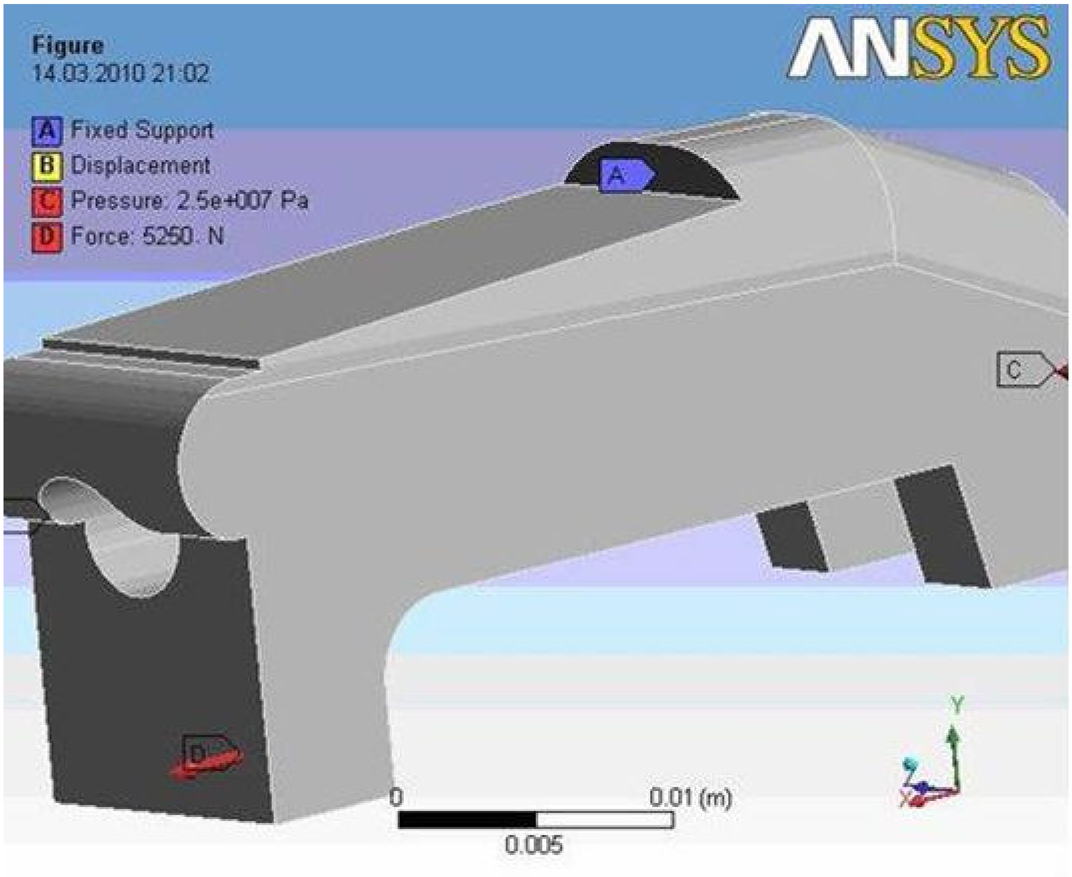

Figure 6. Applied forces and boundary constrains of the locking block.

Table 4. Material properties of AISI 4340 steel for ANSYS analysis.

Young's modulus	205 GPa
Density	7850 kg/m^3
Poisson's ratio	0.29
Yield strength	1350 MPa
Ultimate tensile strength	1467 MPa

martensitic steel heat-treated in achieving the optimum combination of strength, ductility and toughness may result primarily from different processes of heat tempering. This loss in toughness may result primarily from different processes of heat treatment. The manufacturer must avoid tempering between 230 and 370°C because of the blue brittleness.

A comparison of data in Tables 2, 3 and Figure 5 with the heat-treatment data of AISI 4140 and AISI 4340 alloy steels strength, ductility and hardness values, it is clearly indicated that the AISI 4340 alloy steel is better than AISI 4140 alloy steel for locking block material. Best mechanical properties were obtained at 450°C tempering conditions.

Finite element analysis results

After understanding that the best material for locking block is AISI 4340 at 450 °C tempering conditions, locking block geometry was investigated using finite element method ANSYS. The finite element code ANSYS was used to determine the stress distribution in the locking block when subjected to the load and constraints of operational conditions.

When the action bar crashed into the locking block, a uniform pressure 250 MPa was applied to the locking block face and 5250 N was applied to the edge of locking block (e.g. H. Kuzu, Yildiz shotgun factory, Turkey, personal communications). In addition, boundary constraints and forces placed on the locking block were experienced when the action bar crashed into the locking block after cartridge explosion (Figure 6).

The material properties of the locking block used in this analysis are listed in Table 4. The ANSYS analysis mesh consisted of 422446 nodes and 270871 elements (Figure 7). SOLID 187 element type was used to create a mesh structure which was selected from the ANSYS element library.

The magnitude of the stress experienced on the critical zones of the test sample was approximately 1834 MPa

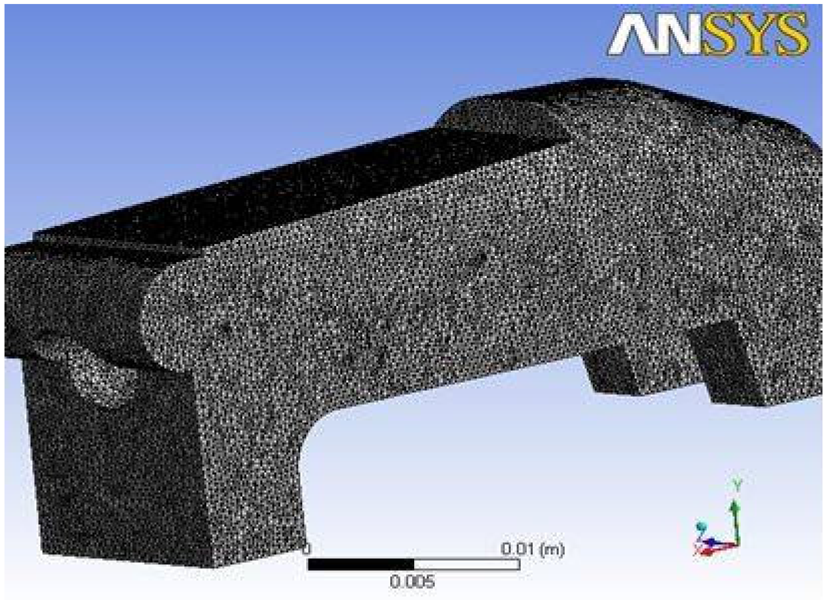

Figure 7. Mesh of locking block.

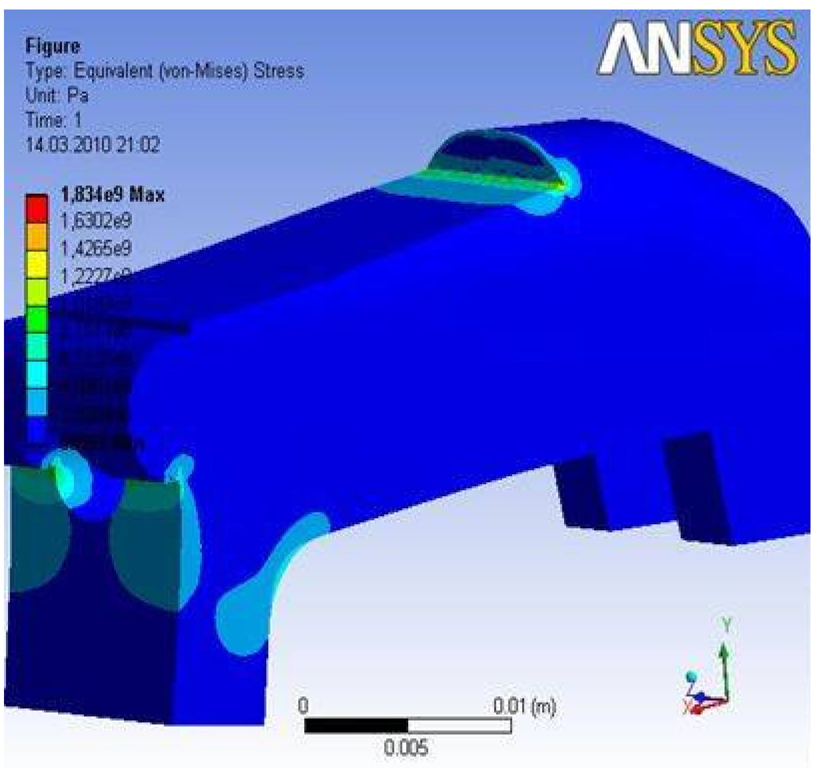

Figure 8. Von-misses stress distribution on the locking block.

from the finite element analysis (Figure 8). This result indicates that the Von-Misses 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. This analysis revealed that over loading has caused the plastic deformation in the critical zones of the part.

Conclusions

Locking block failure in the semi-automatic shotgun bolts is investigated in this study. AISI 4140 and AISI 4340 alloy steels are used as candidate materials for locking block. Mechanical test results show that the best material for locking block is AISI 4340. The best mechanical properties are achieved when the parts tempered at 450 °C.

ANSYS Workbench was used to predict the instantaneous stress value and stress distributions on the locking block. The results obtained from this analysis indicate that high stress concentrations are present at the sharp edges which are located on the rear side of the locking block. One possible counter-measure to prevent locking block failure is to soften the sharp edges of the geometry by appropriate fillet radius.

The authors also recommend decreasing the recoil forces acting on the gun parts by adjusting gas-discharge system in gun design.

ACKNOWLEDGEMENT

Financial support for this study is from the research fund of Pamukkale University under grant No. BAP 2008FBE003 and is gratefully acknowledged.

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