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Dilatometry of Steel for the Production of 5.56 mm Calibre Rifle Barrels

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Abstract. During high rates of fire, the bore of the firearm barrel is exposed to high temperatures. This exposure induces structural changes in the barrel material, which is especially significant for the substrate of the galvanic chrome plating. The alloy steel grades used currently for firearm barrels, when exposed to heating above the ferrite stability limits, develop a phase transition with a discrete negative change in the material volume, which results in typical crazing in the bore. This effect is destructive to the galvanic chrome plating, leading to a loss of adhesion, which reduces the ballistic performance of the firearm, especially its muzzle velocity. This can be prevented by manufacturing barrels from steels having a limited range of phase transitions. The primary method for determining the presence of distinct volume changes in steel due to phase transition is dilatometry over a wide temperature range, which includes the interval within which the barrel bore is heated.

This paper presents the dilatometry results for four steel grades, which included a steel grade currently used for firearm barrels, and an analysis of the effects of phase transition on the degradation of the barrel bore.
Keywords: mechanical engineering, firearm barrels, dilatometry

1. INTRODUCTION

The bores of barrels having galvanic chrome plating are degraded by high rates of use, which exposes the bores to high temperatures leading to changes in the structure of the steel. The key change occurs when the ferrite/austenite phase transition temperature limit is exceeded, which involves a change in the crystal lattice of the alloy. The transition from a ferritic BCC lattice into an austenitic FCC lattice involves a discrete negative change in the material volume. This is demonstrated by the dilatometry tests presented in the papers on the characteristics of steel [1]. The cyclic shrinkage changes in the steel substrate volume lead to cracking and chipping of the chrome plating layer deposited on top. The nature of this wear is present virtually from the start of firearm barrel operation, and reduces the muzzle velocity of projectiles. The structural transformation in the structural steel begins at a temperature of approximately 730°C, which is below the temperature to which the outer layer of the barrel bore is heated. Cross-sections of the barrel bore surfaces during metallographic testing reveals large cracks caused by shrinkage of the material, present beneath the chrome plating. [2]

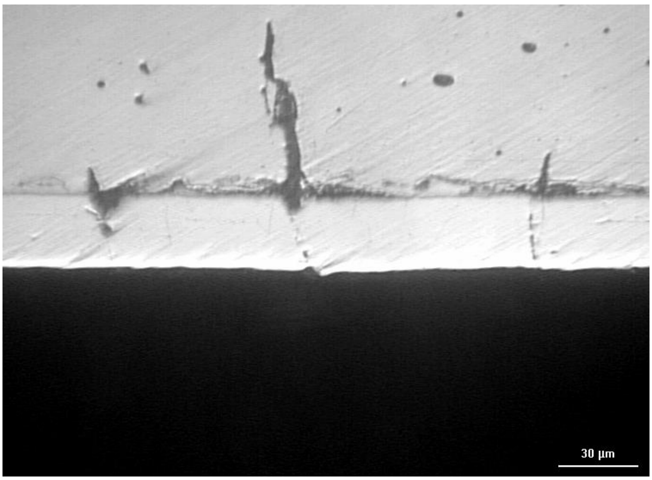

Fig. 1. Metallographic cross-section of a barrel bore surface with characteristic shrinkage voids beneath the galvanic chrome surface. (Specimen unetched)

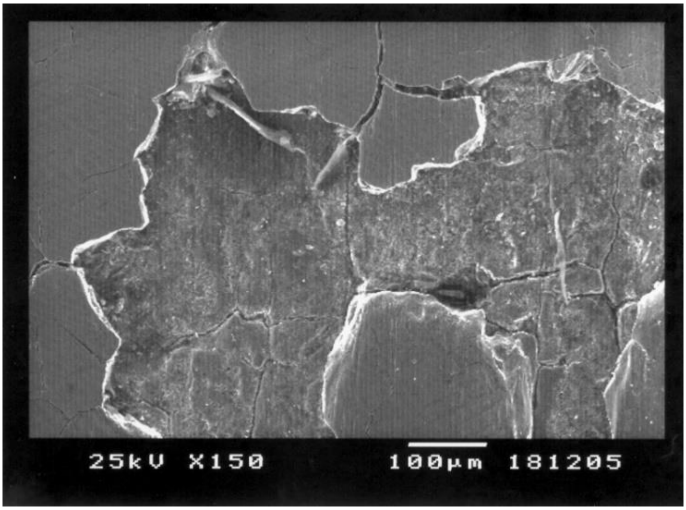

Fig. 2. Image of degraded chrome plating in a barrel bore following high rates of fire based on 1000 ammunition rounds.

The process of galvanic chrome plating of barrel bores has been applied for a long time and has been proven to perform well during operation of firearm barrels for single-shot or short-burst fire. The heat stress in these cases is low enough to prevent structural transformation to the steel substrate. Other advantages of the chrome plating include: corrosion resistance, low wettability with the projectile jacket, and high hardness. However, firing in long bursts involves rapid heating, leading to rapid degradation of the barrel bore surface by detachment of fragments of the chrome plating, resulting in reduced projectile muzzle velocity. Firearm manufacturers have been aware of the phenomena and modifying the production processes of barrels by utilising novel steel grades which provide reduced susceptibility to heat shrinkage and good manufacturability with novel processes for bore surface hardening. [3] Traditional manufacturing processes used alloy steels made highly impact resistant by heat treatment with preservation of the barrel bore through chrome plating. Galvanic chrome plating features relatively weak adhesion to the substrate. Much more durable plating is obtained in processes involving diffusion layer deposition by thermochemical treatment. Because of these issues and to eliminate harmful waste from the chrome plating process, attempts have been made to eliminate and replace galvanic chrome plating with novel methods of barrel bore preservation related to wear, based on thermochemical treatment, where nitriding prevails.

The implementation of nitriding requires replacing the barrel steel grades with those susceptible to thermochemical treatment and with a chemical composition which features such additives as increased contents of chromium, molybdenum, and aluminium with a reduced level of nickel.

In nitrided barrels, high rates of firing cause the nitride layer to chip away from the bore surface by structural changes in the steel material. Compared to chrome plating, the corrosion resistance is worse, with an increased tendency for adhesive deposition of the projectile jacket material on the bore surface. This process was implemented for the M16A1 carbine operated in the first years of the Vietnam war, but not without issues. However, thermochemical processing has developed significantly since the 1970s by the introduction of gaseous phase processes with a controlled nitriding atmosphere potential. The recommended methods for barrel nitriding have evolved to a point where the nitriding potential is set to be low and prevents precipitation of the nitride layer in the process. The superficial layer of the steel forms a solvent zone with a high concentration of nitrogen, while high hardness is provided by nitride inclusions with Al, Cr, and Mo. These processes require the latest control and measurement instruments and have emerged only recently.

A more radical method of improving the durability of firearm barrels was the implementation of new generations of DUPLEX and MARAGING grade steels. MARAGING grade steels (which are hardened by precipitation) are now present in medium-calibre barrels and contribute highly to their extended life. However, the application of maraging steel alloys in 5.56 mm calibre firearms poses several processing challenges: low processability by forging and complicated heat treatment with high costs, which discourages firearm manufacturers from using the material.

This is not so with duplex grade steels, which are common, feature high plasticity, and are the only stainless steel types to meet the requirements for strength, impact resistance, and plasticity. Duplex grade steels have many characteristics typical of galvanic chrome plating: high resistance to corrosion and low adhesion of projectile jacket material. Their resemblance to pure chromium stems from the high concentration of the same element, reaching 22–25%, with considerable contents of Ni (2–5%) and Mo (3%). Instead of a complex galvanic chrome plating process for the barrel bore, the whole barrel assembly can be manufactured from a material which resembles the characteristics of chromium, hence avoiding the issue of chrome plate chipping. An advantage of duplex grade steels is a biphasic ferritic-austenite structure, where only one of the components (the ferrite) is susceptible to high-temperature phase transition. Duplex steel barrels are highly resistant to high rates of fire, as proven by the tests under the research project no.T00B 002 31 0946/2009 [4]. A confirmation of the suitability of various steel types for 5.56 mm calibre barrels could be dilatometry results intended to determine the occurrence of structural transformation, shrinkage types, and the temperature of these phenomena.

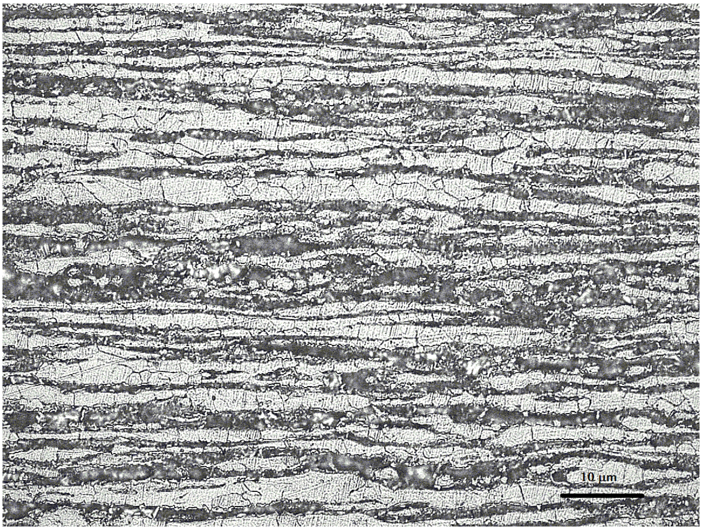

Fig. 3 Structure of grade 14462 duplex steel: light areas are austenite, dark areas are ferrite (etched in copper sulphide and hydrogen chloride)

2. TESTED STEELS

Four steel grades were selected for testing, and included 30HN2MFA, a steel grade already used for production of barrels (this grade has no counterpart under the European standards). Included was 1.8509 grade steel (acc. EN standards) intended for nitriding and which potentially could replace the current steel grade in use, with the addition of a novel thermochemical treatment process of controlled nitriding without precipitation of a nitride phase. Another material was 1.4462 duplex grade steel. Also included in the dilatometry was 1.2709 MARAGING 350 grade steel.

Table 1. Chemical composition of the tested steels

#	Polish standard (PN)	European standard (EN)	Element content [%]									
			Fe	C	Si	Mn	Cr	Mo	Ni	Al	V	Co
1	30HN2MFA	none	96.42	0.29	0.26	0.36	0.65	0.24	2.21	-	0.23	-
2	38HMJ	1.8509	95.21	0.44	0.24	0.54	1.61	0.26	0.19	1.20	-	-
3	none	1.4462 DUPLEX	67.99	0.04	0.33	1.80	21.83	3.14	4.45	-	0.11	-
4	none	1.2709 MARAGING	68.29	0.015	0.05	0.12	-	4.5	17.8	0.11	-	9.4

The 30HN2MFA grade steel has mechanical properties suitable for the production of firearm barrels featuring high impact resistance, resulting in very favourable behaviour of the material under exposure to dynamic increases in pressure concomitant to a cartridge discharge. The hardness level achieved by heat treatment is 28–32 HRC, which enables downstream processing, including forging of the barrel bore. This process ensures a favourable distribution of stress and a higher manufacturing precision of the barrel bore in comparison to deep drilling.

The 1.8509 grade steel (38HMJ) is intended for nitriding. Containing aluminium, chromium and molybdenum, the steel achieves high surface hardness by nitriding, endowing the product with a high abrasive wear resistance. The steel is processed by hardening and high tempering combined with controlled nitriding in a single process. Strength-wise, the steel meets the requirements for firearm barrel materials.

The 1.4462 grade steel is a duplex austenite-ferrite material with high corrosion and acid resistance. It has the strength, impact resistance, and plastic formability sufficient for the production of 5.56 mm calibre barrels. The mechanical properties of duplex steels depend on the austenite to ferrite ratio in the structure; the ratio can be adjusted to a limited extend by heat treatment. Fast cool down from 1300°C retains the austenite in the steel structure, which facilitates plastic working, whereas slow cool down favours precipitation of ferrite.

The 1.2709 grade steel (MARAGING) is a carbon-free, precipitation-hardened alloy. The main alloy additives in the composition include nickel, cobalt, and molybdenum. The heat treatment of this steel is very complex, involving solution and ageing, during which intermetallic phases are separated to strengthen the structure. It is particularly prone to cold-work strengthening, which makes plastic manufacturing difficult, especially forging. It is used for 20 mm calibre anti-aircraft guns and provides a longer life than the previously used alloy steels.

3. DILATOMETRY TESTING OF STEEL

Dilatometry usually involves the determination of the heat expansion coefficient, but it is viable for testing the effects of phase transition. This is based on the specific volume differences manifesting in specific alloy phases. The phase transition is evident by a discrete change of specimen length. The test stand on which the four steel specimens were tested comprised a contact, automatic horizontal dilatometer, type JURA D3, coupled to a data logging system. The dilatometer pusher was brought to contact with the specimen and sensed the increase of specimen length as the temperature increased. A dilatometric chart was plotted for the tested steel.

The dilatometer featured a thermocouple sensor and a compensator to eliminate the effect of heat expansion of measuring components other than the test specimen of steel [5].

The specimens were fabricated as cylinders, with a diameter of 4 mm and length of 40 mm. Each test was carried out during a cycle of heating to 900°C followed by a cooling process lasting approximately 2 hours. The heating rate was 20°C/min, and the specimen and furnace cool down rate was 10°C/min.

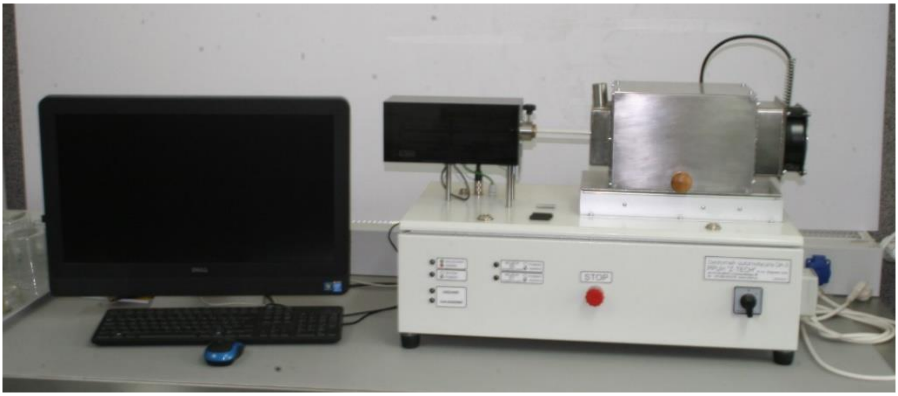

Fig. 4. Overview of the DA-3 automatic dilatometer

4. DILATOMETRY RESULTS FOR STEEL

The results of the dilatometry tests are shown in the chart screenshots generated from the DA-3.

The temperature ranged on the abscissae axis from 0 to 1200°C. The ordinate axis shows the relative length change of the test specimen. The phase transition was manifested on the chart as a distinct change, being a discrete reduction of specimen length. The magnitude of shrinkage was not considered as it depended on the effect of other factors, including grain size or concentration of crystallographic defects. It was only determined for which steel grades the phase transition manifested, highlighting the distinct part of the chart trend with a circle.

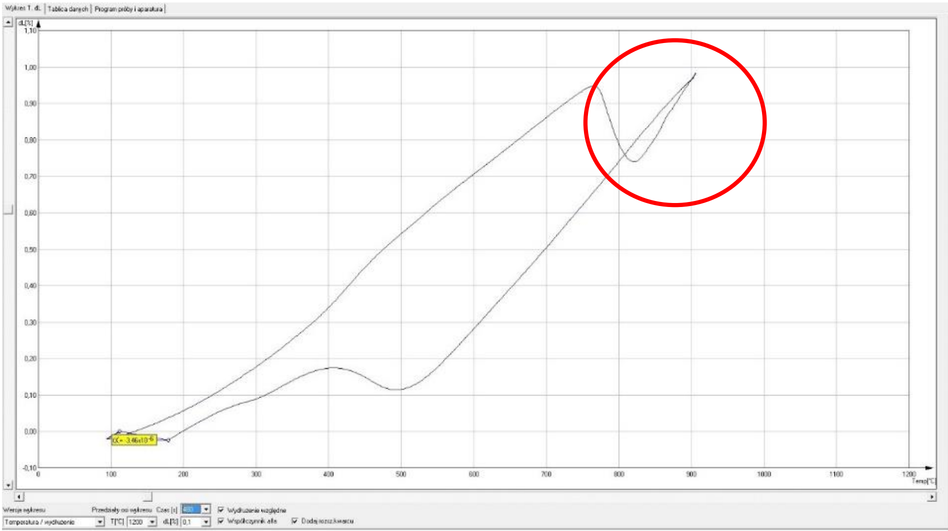

Fig. 5. Dilatometric curve chart for the 30HN2MFA barrel grade steel.
The vertical axis shows the relative dimensional changes of the sample ranging from 0-1[%]. Temperature range on the horizontal axis 0-1200 ºC.

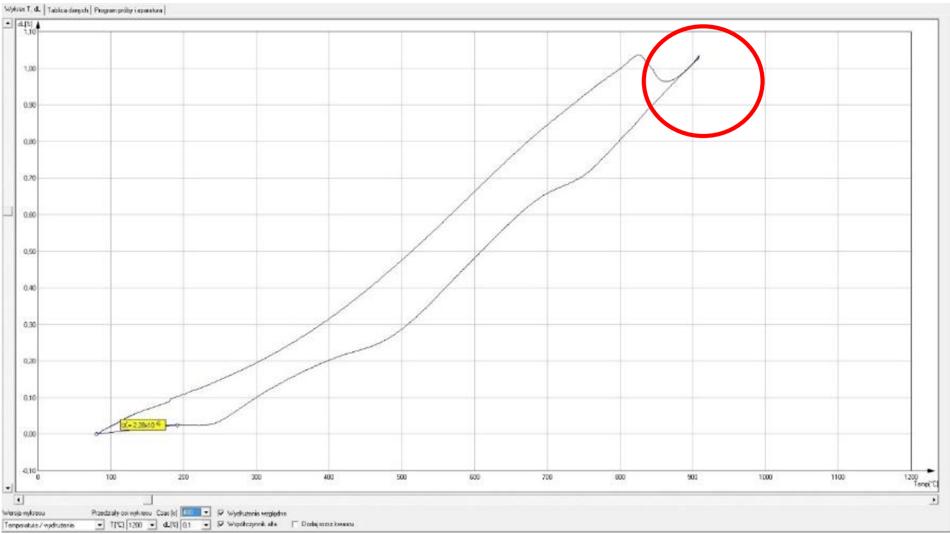

Fig. 6. Dilatometric curve chart for the 1.8509 nitriding grade steel.
The vertical axis shows the relative dimensional changes of the sample ranging from 0-1,3 [%]. Temperature range on the horizontal axis 0-1200 ºC.

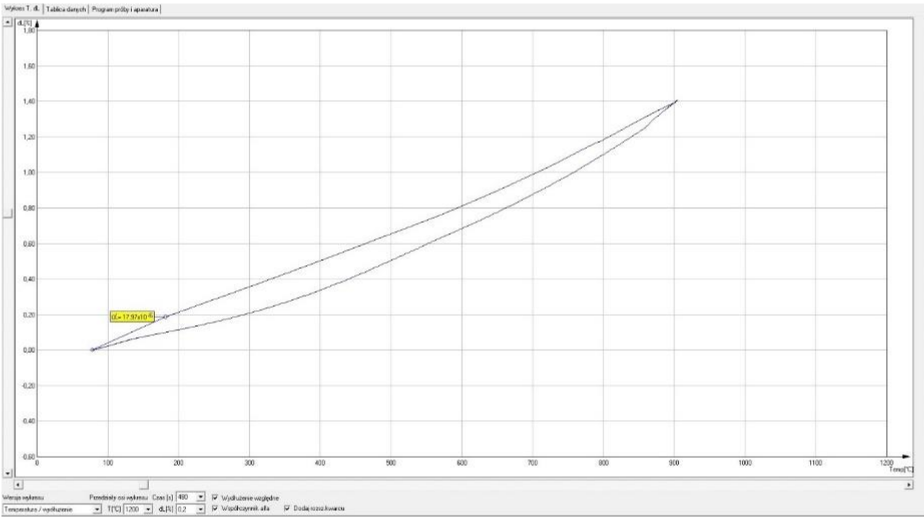

Fig. 7. Dilatometric curve chart for the 1.4462 DUPLEX grade steel.
The vertical axis shows the relative dimensional changes of the sample ranging from 0-1,6 [%]. Temperature range on the horizontal axis 0-1200 ºC.

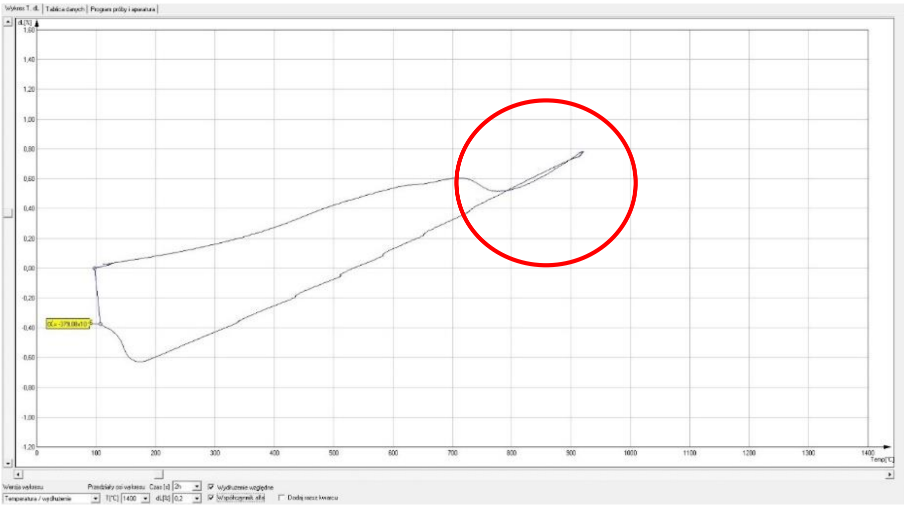

Fig. 8. Dilatometric curve chart for the 1.2709 MARAGING grade steel.
The vertical axis shows the relative dimensional changes of the sample ranging from 0-1,6 [%]. Temperature range on the horizontal axis 0-1400 ºC

The encircled areas for all steel grades aside from the DUPLEX steel revealed a shrinkage caused by phase transition. It was especially large on the dilatometric curve of the 30HN2MFA grade steel, resulting in a degradation of the galvanic chrome plating on the barrel bore, as explained in the background. The phase transition temperature for 30HN2MFA was 770°C and consistent with the equilibrium system. For the 1.8509 nitriding grade steel, the phase transition temperature was 60°C higher, reaching 830°C.

The application of this grade steel would provide barrel material stability at higher temperatures. Of all the tested steel grades, only DUPLEX 1.4462 did not reveal any phase transition-related shrinkage. Hence it should not develop any crazing when used as a barrel bore material. The dilatometric test results for the 1.2907 MARAGING grade steel revealed a phase transition at 720°C, which was lower than for the alloy steels. The change was much smaller than for the compared steel grades, and resulted from a high concentration of nickel which stabilised the austenite.

5. CONCLUSIONS

1) Among the tested steel grades, 30HN2MFA developed the highest shrinkage from the ferrite/austenite phase transition, resulting in detachment of the chrome plating layer from the bore during high rates of fire.
2) The 1.8509 nitriding grade steel suffered smaller shrinkage at a temperature higher than for 30HN2MFA.
3) The 1.4462 DUPLEX grade steel did not have any shrinkage from the ferrite/austenite phase transition, which favours a lower wear rate of the barrel bore.
4) The 1.27909 MARAGING grade steel suffered a small effect of the phase transition on the specimen dimensions.
5) Replacing the 5.56 mm calibre barrel material with the DUPLEX grade steel would increase the life of the barrel during intensive operation.

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Badania dylatometryczne stali do produkcji luf 5,56 mm

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Streszczenie. Podczas intensywnego strzelania przewód lufy broni strzeleckiej jest narażony na działanie wysokiej temperatury. Powoduje to przemiany strukturalne szczególnie intensywne w podłożu pod warstwą chromu galwanicznego. Stosowane obecnie stale stopowe podczas nagrzewania do temperatur powyżej stabilności ferrytu charakteryzują się przejściem fazowym ze skokową ujemną zmianą objętości materiału, która powoduje powstanie w przewodzie lufy typowej siatki spękań. Ma to destrukcyjny wpływ na powłokę chromu galwanicznego, skutkuje utratą jej przyczepności a co za tym idzie pogorszeniem parametrów balistycznych broni; szczególnie prędkości wylotowej. Można temu przeciwdziałać wprowadzając do produkcji luf stale o ograniczonym zakresie przemian fazowych. Podstawowym sposobem ustalenia czy w stali występuje wyraźna zmiana objętości związana z przemianą fazową są badania dylatometryczne w szerokim zakresie temperatur obejmujący zakres, do którego nagrzewa się przewód lufy. W artykule przedstawiono wyniki badań dylatometrycznych czterech stali, w tym stosowanej obecnie i przeanalizowano wpływ przemian fazowych na degradację przewodu lufy.

Słowa kluczowe: inżynieria mechaniczna, lufy, badania dylatometryczne