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# Selected Properties of Input Stock Material for the Production of Thin-Walled Cylindrical Products by Cold Flow Forming

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**Abstract.** This paper presents test results for the steel grade 15HGMV metallurgical purity, microstructure, method of production and effect on the mechanical performance of the input stock material for calibre 227 mm missile motor casings manufactured by cold flow forming.

This work has been compiled from the paper presented during the 12th International Armament Conference on Scientific Aspects of Armament & Safety Technology, Jachranka, Poland, September 17-20, 2018

The reference product for the determination of preliminary design criteria of missile casings of the higher calibre were calibre 122 mm missiles manufactured in Poland. The final mechanical properties of the casings are a cumulative effect of quenching and tempering and strain hardening during cold flow forming. The research and industrial practice carried out so far have demonstrated that the production process of a Feniks missile (with a 1.5 mm thick casing wall) requires steel grades of extremely high purity. This steel grade is manufactured by VAD (*Vacuum Arc Degassing*) melting, followed by ESR (*ElectroSlag Remelting*) or, alternatively by melting and casting in vacuum oven. The content of hard and non-deformable non-metallic inclusions such as oxides is critical to the success of cold flow forming. The cal. 227 mm missile casings feature walls approximately 2.5 mm thick and produced by cold flow forming from a quenched and tempered intermediate product. New material specifications should be developed for this reason to enable correct cold flow forming and contribute to a significant improvement in the cost efficiency of manufacturing. The investigations covered herein were guided by an assumption that the thicker wall sections might make the material specifications applicable to lower-calibre missiles to restrictive and obsolete about cal. 227 missiles. After initial laboratory tests, this hypothesis will be verified in industrial experiments on the production of prototype missile casings from input stock materials varying in metallurgical purity.

**Keywords:** materials engineering, rocket casing, manufacturing

# 1. INTRODUCTION

In the second half of the 1990s, it was decided to implement an upgrade of the Grad missile and thus increase its striking range to over 30 km without modifying its BM-21 launch system. This required the development of a new steel grade of improved strength to permit the use of rocket fuel with a higher energy value. New material specifications were defined, and processes of missile body casing fabrication and heat treatment were proposed. The first development deliverables were presented during a conference in Kołobrzeg, Poland [1]. The 3rd International Armament Conference in Waplewo (Poland) was the forum which outlined the results of the microstructure and the mechanical properties of a novel steel grade proposed under code 15HGMV [2]. The development work defined the micro and macrostructure of the material, the austenite grain growth curves, the hardenability and tempering curves, the phase transition diagram, and the mechanical properties developed by quenching and tempering at various heat treatment processing parameters [2]. As a result of the modification of the manufacturing of intermediates, the two-part casing of the missile motor was replaced with a solid casing [3]. Further work was focused on the development of the manufacturing process for the missile casings of larger diameters [4, 5, 6]. The novel steel grade 15HGMV replaced steel grade Bw13GNA in several stages. In industrial processing conditions, three types of heat were fabricated over several years.

These heat types resulted, on the one hand, from the processing capabilities of the domestic steelmaking industry and, on the other hand, corresponded to the-then demands of customers.

The first heat was made in an arc furnace with external vacuum treatment and modification of inclusions with calcium (Ca). The heat was cast into ingot moulds with the molten steel stream shielded with casting powder (Heat 1, manufactured with VAD - *Vacuum Arc Degassing*). The ingots, each one ton in weight, were rolled into square billets with a cross-sectional length of 135 mm [2]. The second heat (Heat 2, manufactured with VAD+ESR) was produced in the same conditions as applied to Heat 1, followed by ESR (*ElectroSlag Remelting*) of one-ton ingots cast from the heat. The ingots were then rolled into slabs for hot forging.

The third industrially-manufactured heat (Heat 3, manufactured with OIM-ESR) (OIM: *Open Induction Furnace Melting*) was made by melting steel in an open induction furnace, followed by traditional casting into one-ton electrode ingots which were rolled into thick-walled pipes [4, 6]. From each of the three heats, intermediates were fabricated to produce missile motor casings according to different processing schemes [6-8]. The final processing operation applied to every intermediate produced was cold flow forming following quenching and tempering. This provided the casing with the final mechanical and performance properties.

During the first industrial tests of cold flow forming of the casings, the material from Heat 1 had a suboptimal distribution, number and types of non-metallic inclusions the sizes of which caused the casings to fail during cold forming. An additional processing operation was added to improve the purity of the steel: ESR [7], which was indispensable to intermediate products slated for cold flow forming into casings with walls 1.5 mm thick. The research published in [7] suggests that ESR steel (and irrespective of the manufacturing process of ingots) forms refined and uniformly distributed non-metallic inclusions, each less than ten-odd micrometres in size (Heats 2 and 3).

Given the higher wall thickness of cal. 227 missile motor walls, the feasibility of eliminating the expensive ESR process was analysed. The objective of this work was to follow laboratory testing of cold flow forming and select the parameters of the input stock material for cold roll forming of thin-walled steel cylindrical products in the form of motor casings for cal. 227 mm missiles.

## 2. TEST MATERIAL

The project titled “Auxiliary solid fuel motors for liquid-fuel propelled launch-vehicle rockets”, carried out by a consortium a member of which is MESKO S.A. (Poland), included the planning of the production of experimental steel casings for cal. 227 mm missile motors.

The production was carried out by VAD, arc melting of the heat with external vacuum processing and modification of non-metallic inclusions.

The heat was then cast into ingots. The chemical composition of the resulting material is shown in Table 1. A part of the same heat was processed by ESR. ESR reduced the contents of S, Si and Al. The elements form inclusions of sulphides and oxides, and several complex inclusions. Oxide inclusions are especially harmful to cold forming due to their high hardness and limited deformability. Sulphide inclusions are elongated during cold forming and contribute to the growth of anisotropic mechanical properties. Thick-walled pipes produced for the cold flow forming process were made from ESR-processed stock and non-ESR processed stock. Sections of the pipes were machined, and heat treated by oil quenching and high-temperature tempering. The mechanical properties provided by quenching and tempering should facilitate the production of the required final properties of the motor casings by further strain hardening caused by cold flow forming.

Table 1. Chemical composition of test material, % (w/w)

| Steel grade | C | Mn | Si | P | S | Cr | Ni | Mo | Al |
|---|---|---|---|---|---|---|---|---|---|
| **15HGMV** | 0.17 | 0.93 | 0.11 | 0.011 | 0.005 | 1.43 | 0.09 | 0.88 | 0.039 |
| **15HGMV-ESR** | 0.17 | 0.92 | 0.05 | 0.011 | 0.002 | 1.43 | 0.09 | 0.88 | 0.019 |

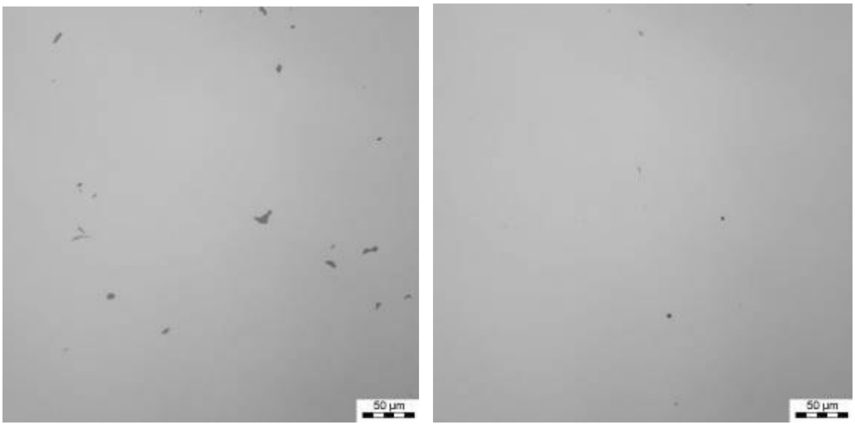
To select the parameters of the input stock material for the cal. 227 mm missile motor casings manufactured by cold flow forming, the following laboratory and industrial tests were planned for the ESR and non-ESR processed material:

- Testing of microstructure, non-metallic inclusions, mechanical properties and hardness of cold flow forming intermediates;
- Cold formability tests within the range of strain rate from 1 $s^{-1}$ to 50 $s^{-1}$ on a Gleeble simulator machine;
- Analysis of mono-axial compression curves at the strain rate of 1-50 $s^{-1}$;
- Testing of non-metallic inclusions, microstructure and hardness in specimens formed on the Gleeble simulator machine.

The paper provides the results of laboratory tests which guided the definition of material specifications required for the input stock material intended for industrial cold flow forming tests. The tests focused specifically on the cold formability of the material and the behaviour of its non-metallic inclusions. The material from the cold flow formed castings will be tested in detail for non-metallic inclusions, microstructure and mechanical properties to verify the laboratory test results of cold formability. The industrial input stock material was in the process of preparation for cold flow forming at the time of writing this paper.

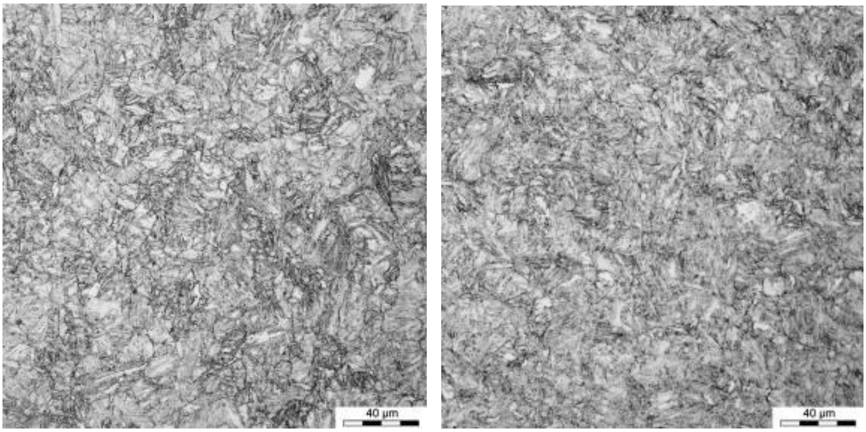
## 3. TESTING OF THE NON-METALLIC INCLUSIONS AND OF THE MICROSTRUCTURE FOLLOWING QUENCHING AND TEMPERING

Once quenched and tempered, steel grade 15HGMV was intended for cold flow forming. This required a specific metallurgical purity in addition to certain mechanical properties. The critical factors were the number and size of inclusion, the type of inclusion and the uniformity of distribution of inclusions. Figure 1 shows examples of microstructural photographic images of non-metallic inclusions present in the tested ESR and non-ESR processed steel grade 15HGMV.



(a) (b)

Fig. 1. Non-metallic inclusions in steel grade 15HGMV
(a) Non-ESR processed material; (b) ESR-processed material



(a) (b)

Fig. 2. Microstructure of steel grade 15HGMV following quenching and tempering (austenitized at 970°C and oil-cooled with tempering at 660°C)
(a) Non-ESR processed material; (b) ESR-processed material

The ESR-processed input stock material featured a very low content of inclusions, while the size of oxygen inclusions was up to 5 μm only. The non-ESR processed input stock material featured much more inclusions, and the size of oxide inclusions, sulphides and complex inclusions was up to 30 μm (Fig. 1b).

The microstructures of the ESR and non-ESR processed materials, comprising tempered martensite and bainite, were not significantly different (Fig. 2).

## 4. TESTING OF MECHANICAL PROPERTIES FOLLOWING QUENCHING AND TEMPERING

The mechanical properties of the intermediate products intended for cold flow forming were tested on round-section test strength specimens sized ϕ10xM16 mm cut from pipes that were rolled from ESR and non-ESR processed input stock materials. The strength test specimens were quenched, followed by tempering at 680°C, 660°C, and 640°C. Table 2 lists the test results of static strength testing and hardness testing.

Table 2. Mechanical properties and hardness of the intermediates for the cold flow forming of casings (following quenching and tempering, austenitized at 970°C and oil-cooled; $T_o$ is the tempering temperature)

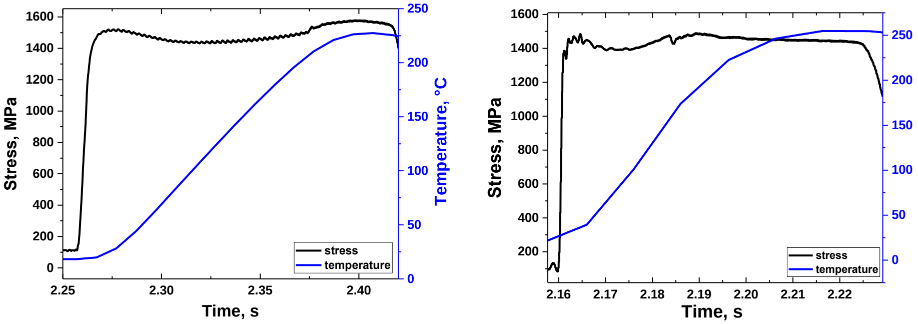
| **Material designation ($T_o$, °C)** | **Yield strength, $R_{p02}$** | **Tensile strength, $R_m$** | **Percentage elongation, $A_5$** | **Hardness** |
|---|---|---|---|---|
| | **MPa** | **MPa** | **%** | **HV** |
| 680/ESR | 1003 | 1047 | 18.1 | 343 |
| 680/NON-ESR | 998 | 1044 | 17.9 | 343 |
| 660/ESR | 1070 | 1126 | 18.0 | 362 |
| 660/NON-ESR | 1079 | 1131 | 17.1 | 364 |
| 640/ESR | 1131 | 1208 | 17.2 | 389 |
| 640/NON-ESR | 1107 | 1211 | 17.2 | 389 |

The test results led to the conclusion that the application of ESR did not affect the strength, elongation or hardness of the intermediate products intended for cold flow forming.

# 5. COLD FORMABILITY TESTING ON THE GLEEBLE SIMULATOR MACHINE

The effects of the method of input stock material preparation on cold flow forming were determined by testing on a Gleeble simulator machine. Only quenched and tempered material was tested. Cylindrical specimens with a diameter of ϕ5 mm were mono-axially compressed at strain rates of 1, 10 and 50 s$^{-1}$. The specimens were not cooled during the tests.

The temperature of the side walls of the specimens during these tests was found to reach the following values: 110-130°C, 200-240°C and 230-255°C at the strain rate of 1, 10 and 50 s$^{-1}$, respectively (Fig. 3). These temperature rise limits on the side walls indicated that the internal specimen temperatures were much higher.



(a ) (b)

Fig. 3. Temperature changes on the specimen surface and the stress during the compression test at (a) 10s$^{-1}$, $T_o$ = 640°C/non-ESR; (b) 50 s$^{-1}$; $T_o$ = 640°C/ESR Steel grade 15HGMV

Figure 4 shows an example of the compression curves of the ESR and non-ESR processed materials deformed at the strain rates of 1, 10 and 50 s$^{-1}$.

Distinct strain hardening of the material (at up to 1700 MPa maximum) was found during the compressive tests at the strain rate of 1 s$^{-1}$. The stress increase was not found to be different between the ESR and non-ESR processed materials.

At higher strain rates, the stress would decrease (also due to the temperature rise in the specimen and the strain location), resulting in a strain hardening much lower than produced in the specimens strain-hardened at 1 s$^{-1}$. Note that during mono-axial compression, an increase of the strain rate resulted in an increase in the probability of local deformations.

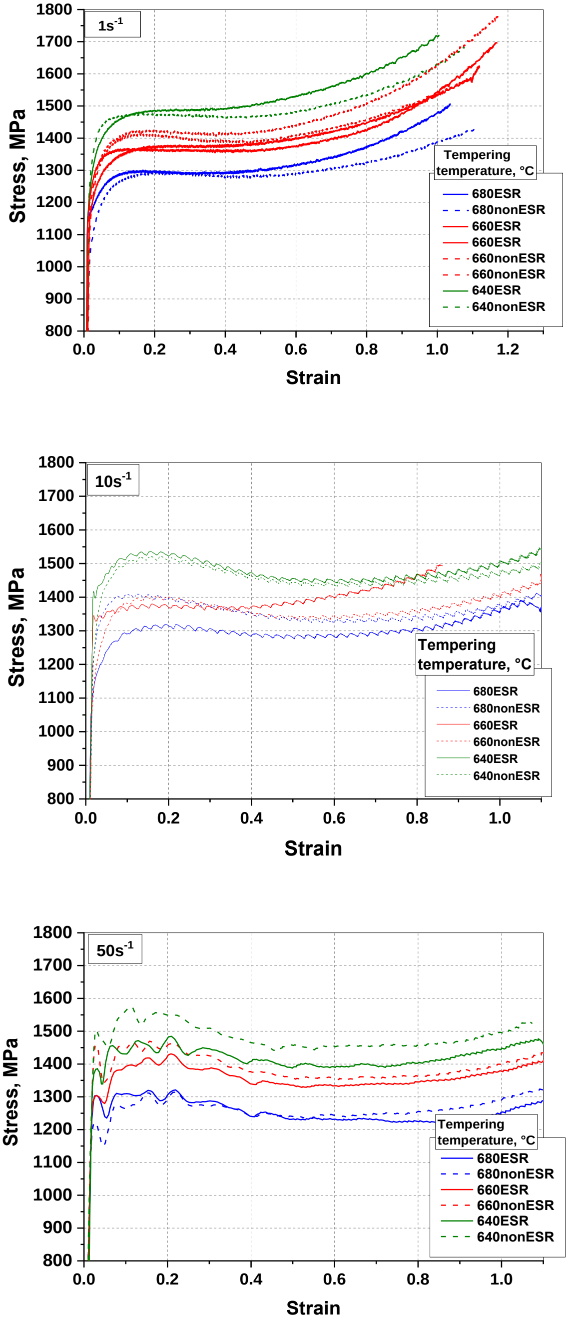


Fig. 4. Compression curves for the steel grade 15HGMV strained at ambient temperature at the strain rate of 1 $s^{-1}$, 10 $s^{-1}$ and 50 $s^{-1}$

## 6. TEST RESULTS OF HARDNESS FOLLOWING QUENCHING AND TEMPERING AND COLD FORMING

The magnitude of strain hardening was determined by hardness testing on the cross-sectional surfaces of the specimen axis (i.e. in the middle of specimen height). Following the cold upsetting test, HV10 hardness of the specimens was tested. Figure 5 shows the hardness test results for the specimens processed at a strain rate of 1 $s^{-1}$.

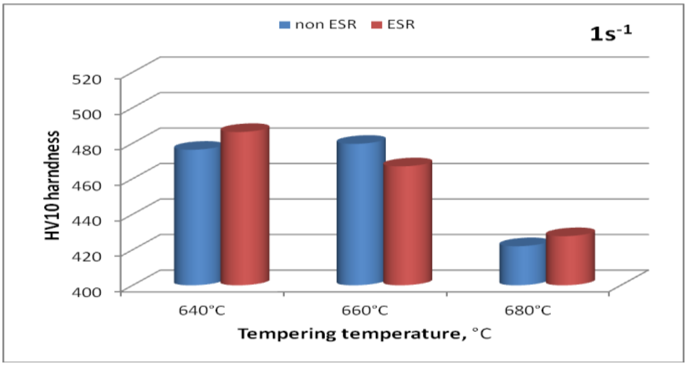


Fig. 5. Hardness of the specimens after mono-axial compression on the Gleeble simulator machine

A significant reduction in hardness was found to be concomitant to the increase of tempering temperature from 660°C to 680°C. There was no effect of the input stock material preparation (with or without ESR processing) on the strain hardened material hardness. Figure 6 lists the hardness test results for the strain-hardened specimens in reference to the quenched and tempered material (QTM). The mean hardness was found to have risen to 60 HV at tempering temperatures of 680°C, 660°C and 640°C at the strain rates of 1 to 50 $s^{-1}$.

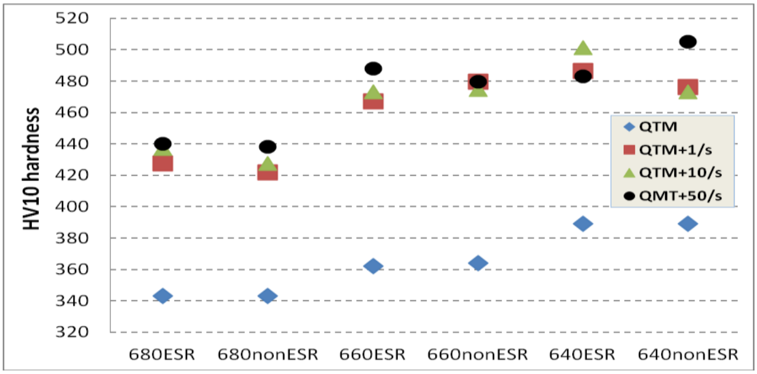


Fig. 6. Hardness changes from cold mono-axial compression at the strain rates of 1, 10 and 50 s-1

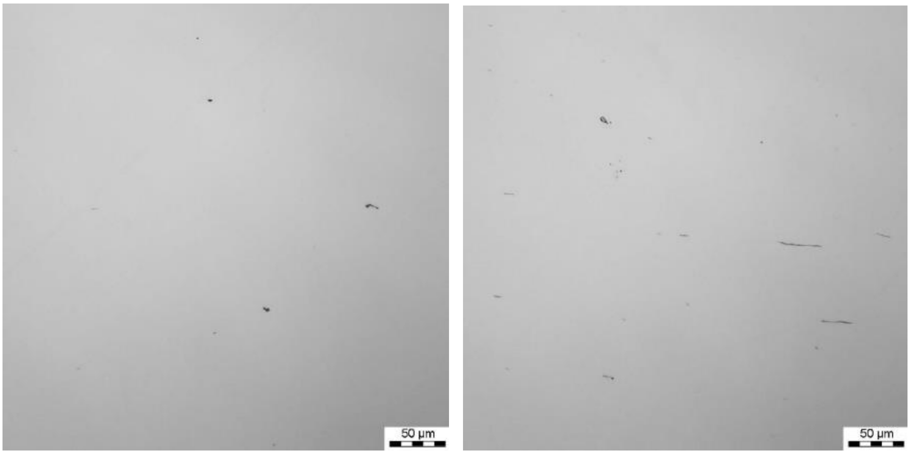
There was no significant difference in the hardness increase (the quantitative effect of strain hardening) between the ESR and non-ESR processed materials.

## 7. TESTING OF THE NON-METALLIC INCLUSIONS AND MICROSTRUCTURE FOLLOWING QUENCHING AND TEMPERING AND COLD FORMING

The behaviour of the non-metallic inclusions during cold forming by mono-axial compression was tested under a light microscope.

This analysis specifically focused on hard, non-deformable oxide inclusions which may cause superficial defects in products made by cold flow forming. When compressed, a tested sample developed a multi-axial state of stress. The material is exposed to tensile stresses propagating in perpendicular to the direction of compression. Figure 7a shows an example of non-metallic inclusion in an ESR-processed material specimen following compression at $1s^{-1}$. The content and shape of inclusions were found to be approximate to those of the material prior to the compression test. There were sporadic non-deformed oxide inclusions and/or slightly elongated oxide-sulphide inclusions less than 5 μm in size. The non-ESR processed material specimens featured heavily elongated manganese sulphides or (Fe,Mn)S and non-deformed primary oxides with a size between 10 and 20 μm (Fig. 7b). Inclusions in the form of hard, non-deformable solids with a size of over 10 μm could become stress concentrators during cold flow forming.

Hard oxide inclusions could prevent the production of thin-walled casings by shearing through the material during the simultaneous advance, rotation and plastic strain caused by cold flow forming.

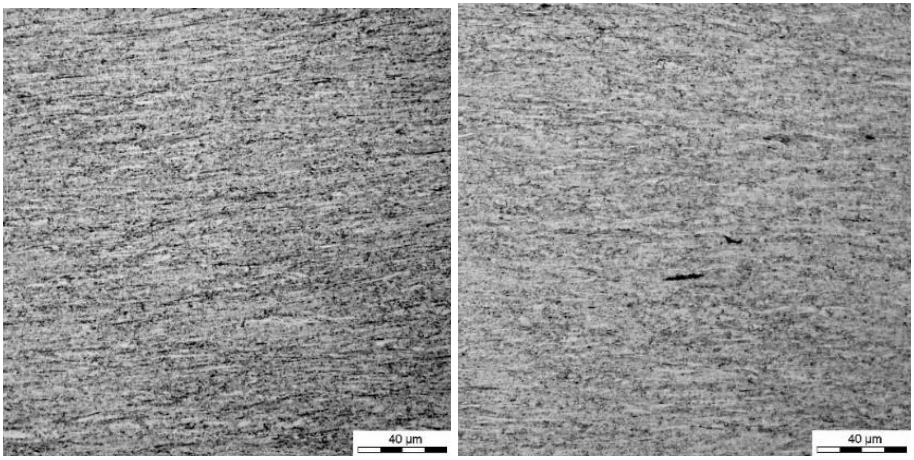


(a) (b)

Fig. 7. Non-metallic inclusions following cold forming of (a) ESR-processed material and (b) non-ESR processed material. Tempering temperature: 660°C; strain rate: 1 $s^{-1}$

The microstructure of the tested material versions featured similar morphologies and uniformities (Fig. 8). It comprised heavily elongated bars of bainitic ferrite and bars of martensite.

The tests performed on the as-strain-hardened material found no microfracture or void, especially around non-metallic oxides.



(a) (b)

Fig. 8. Microstructure images of the specimens following cold forming (strain hardening). (a) ESR processed material and (b) non-ESR processed material; tempering temperature: 660°C; strain rate: 1 $s^{-1}$

## 8. CONCLUSION

This paper shows the definition of the material specifications for steel grade 15HGMV, intended to produce experimental motor casings of cal. 227 mm missiles by cold flow forming. Laboratory test results were provided for the cold deformability (strain hardenability) of specimens fabricated from steel grade 15HGMV which was either processed or unprocessed by ESR. Non-metallic inclusions, microstructure and hardness of the specimens were tested.

The plastic flow charts were plotted for the specimens during compression at strain rates in a range of 1-50 $s^{-1}$.

There were no significant differences in microstructure, hardness and mechanical properties (including strain hardening by mono-axial compression) between the tested material versions (the ESR and non-ESR processed specimens). The only significant difference found was the form and size of non-metallic inclusions in the as-strain hardened materials. The hardly deformable and hard oxide solids present in the non-ESR material version were ten-odd μm in size and could inhibit the production of thin-walled motor casings of the specified quality.

The casings in the form of hard grains at critical sizes were stress concentrators and could also prevent the production of the thin-walled casings due to the effect of shearing through the input stock material during the simultaneous advance, rotation and plastic strain caused by cold roll forming.

The state of stress and strain found during the mono-axial compression tests only partially matched the multi-axial state generated by cold flow forming. This requires a verification of strain hardenability of the materials in industrial testing of cold flow forming.

The project plans provide to produce experimental missile motor casings by cold flow forming of the two already tested material versions. The resulting test results and material research will allow a specification of the production of intermediate materials for the cold flow forming of the motor casings of cal. 227 mm missiles.

## FUNDING

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# Wybrane właściwości materiału wyjściowego do wytwarzania cienkościennych stalowych wyrobów cylindrycznych metodą zgniatania obrotowego

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**Streszczenie.** W artykule przedstawiono wyniki badań czystości metalurgicznej stali 15CrMoV6-10-3 (15HGMV), mikrostruktury, sposobu jej uzyskania i wpływu na właściwości mechaniczne materiału przeznaczonego do wytwarzania eksperymentalnych korpusów silników rakiet kalibru 227 mm metodą zgniatania obrotowego na zimno. Produkowane w kraju rakiety kal. 122 mm stanowiły wyrób odniesienia do określenia wstępnych wymagań dla korpusów rakiet większego kalibru. Finalne właściwości mechaniczne korpusów są sumarycznym efektem ulepszania cieplnego i umocnienia odkształceniowego w procesie zgniatania obrotowego na zimno. Dotychczas przeprowadzone badania i praktyka przemysłowa, wykazały, że wytworzenie korpusu rakiety Feniks (o grubości ścianki ok. 1,5 mm) wymaga bardzo wysokiej czystości stali, którą uzyskuje się w procesie wytapiania w piecu elektrycznym z próżniowym odgazowaniem i następnym przetopem elektrożużlowym lub alternatywnie w procesie wytapiania i odlewania w piecu próżniowym. Szczególnie istotna w trakcie zgniatania obrotowego jest zawartość twardych nieodkształcalnych wtrąceń niemetalicznych takich jak tlenki. Korpusy rakiet 227 mm charakteryzuje ścianka o grubości ok. 2,5 mm uzyskiwana metodą zgniatania obrotowego z półwyrobu ulepszonego cieplnie. Z tego powodu należy opracować nowe wymagania dla materiału do poprawnego przeprowadzenia procesu zgniatania obrotowego, które mogą przyczynić się do istotnej redukcji kosztów wytwarzania. Podejmując zagadnienie stwierdzono, że ze względu na większe grubości ścianek korpusów rakiet 227 mm, stosowanie dla nich wymagań dotyczących mniejszych kalibrów może być zbyt restrykcyjne i niekonieczne. Hipoteza ta po przeprowadzeniu wstępnych badań laboratoryjnych zostanie zweryfikowana na podstawie wyników eksperymentów przemysłowych wytwarzania prototypowych korpusów z materiałów o zróżnicowanym poziomie czystości metalurgicznej.

**Słowa kluczowe:** inżynieria materiałowa, korpus silnika, rakieta, wytwarzanie