A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 58 2013 Issue 2
DOI: 10.2478/amm-2013-0040

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ANALYSIS OF THE INFLUENCE OF DRAWING PROCESS PARAMETERS ON THE MECHANICAL PROPERTIES OF TRIP-STRUCTURE STEEL WIRES

ANALIZA WPŁYWU PARAMETRÓW PROCESU CIĄGNIENIA NA WŁASNOŚCI MECHANICZNE DRUTÓW ZE STALI O STRUKTURZE TYPU TRIP

The research concerned with wire drawing processes of medium-carbon steel with TRIP effect classified into group of AHSS (Advanced High Strength Steel) steels, which are the multiphase steels offering a unique combination of high strength and ductility, has been shown in the work. Such combination is achieved through the transformation of retained austenite to martensite in deformation process called TRIP effect (Transformation Induced Plasticity).

Studies reported in the literature relate mainly to the research on the car body sheet rolling and heat treatment processes, which does not allow the results of this research to be referred to the analysis of drawing processes.

Therefore, the need has arisen for developing and conducting comprehensive studies on the process of drawing TRIP steels wires and identification the new application areas for these materials.

Keywords: TRIP steel, wire, drawing process

W pracy przedstwiono badania dotyczące procesu ciągnienia drutów ze stali typu TRIP zaliczanej do grupy stali AHSS (Advanced High Strength Steel), charakteryzującą się wyjątkową kombinacją pomiędzy własnościami wytrzymałościowymi a plastycznością. Korzystna korelacja własności zostaje w tych stalach osiągnięta w wyniku przemiany austenitu szczątkowego w martenzyt w procesach odkształcenia, i nosi miano efektu TRIP (Transformation Induced Plasticity).

Zawarte w literaturze opracowania dotyczą głównie badań nad procesami walcowania i obróbki cieplnej blach karoseryjnych, co nie pozwala na odniesienie wyników tych badań do analizy procesów ciągnienia. W procesie ciągnienia zarówno wielkości odkształcenia całkowitego, jak i prędkości odkształcenia są wielokrotnie wyższe, co znacząco wpływa na obecność efektu TRIP, a co za tym idzie na własności materiału.

Zaistniała zatem konieczność opracowania i przeprowadzenia kompleksowych badań procesu ciągnienia drutów ze stali z efektem TRIP oraz określenia nowych obszarów zastosowań dla tego typu materiałów.

1. Introduction

The drawing process is a complex process in which the selection of the optimal parameters, that is the drawing speed and the magnitude of partial drafts and the total draft, has a significant effect on the properties of final wires [1-4].

The determination and selection of partial drafts is an issue that is dependent on numerous factors, and especially on the properties and structure of material being plastic formed. Wires of hard-deformable and high-carbon steel are normally drawn with smaller partial drafts to enable finished product of proper plastic properties to be obtained. This relationship is reverse for low-carbon steel wires, which are drawn with large partial drafts (above 20%) [5].

The unique properties of TRIP type steels are achieved thanks to the phenomenon of extra plasticity occurring at the time of transformation of the metastable retained austenite into martensite during plastic deformation [6-8].

Published studies on high-alloy austenitic TRIP steels prove the influence of strain intensity and strain rate, chemical composition, and deformation temperature on the effectiveness of the martensitic transformation [9].

The available literature lacks publications concerned with the effect of drawing process parameters on the evolution of the structure of medium-carbon TRIP steel. The investigation described below was carried out on the assumption that: the strain intensity is determined by the magnitudes of partial drafts and the total draft applied, while the strain rate value is the result of the drawing speed used in individual drawing speeds.

2. Research

1. Examination of the influence of drawing process parameters on the mechanical properties of TRIP-structure steel wire.

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The preliminary research carried out by the author, indicates that the quantity of retained austenite transformed into martensite is influenced chiefly by effective strain and also, to some extent, by strain rate [10]. These parameters are determined in the drawing process by the magnitude of partial reduction, the total reduction of area and drawing speed.

At the same time, the amount of the martensite that has formed upon the retained austenite transformation significantly influences the strain hardening of the material, and consequently the mechanical properties of the wire.

Therefore, tests were carried out to determine the effect of the partial reduction magnitude and drawing speed on the mechanical properties of TRIP steel wire [10].

Wire rod of a diameter of 6.25 mm was used for the tests. In order to obtain the TRIP structure, the wire rod was heat treated under laboratory conditions in resistance heating furnaces manufactured by LAC, according to the parameters established in the previous tests, which allowed a maximum amount of retained austenite (approx. 23%) to be obtained in the structure [11].

The wire rod was subjected to the process of drawing from the initial diameter of 6.25 mm to a final diameter of 2.60 mm, following to drawing variants (Variant 1 - small partial reductions; Variant 2 - large partial reductions; see Table 1), while applying two drawing speeds: $v_1 = 0.23$ m/s and $v_2 = 1.11$ m/s. The drawing was carried out on a JP600 block drawing machine using conventional drawing dies of an angle of $2\alpha = 12°$.

TABLE 1

A summary of partial reductions and the total reduction in area applied for the wire drawn from ø6.25 mm to ø2.60 mm [10]

Wire diameter, mm	Variant 1, G_{pr}, %	Variant 2, G_{pr}, %	G_c, %
6.25	-	-	-
5.60	19.71	-	19.71
5.34	9.07	27.00	27.00
4.95	14.07	-	37.27
4.60	13.64	25.79	45.38
4.22	15.83	-	54.41
3.98	11.05	25.13	59.44
3.70	13.57	-	64.95
3.44	13.56	25.29	69.70
3.18	14.54	-	74.11
2.97	12.77	25.45	77.41
2.78	12.38	-	80.21
2.60	12.53	23.36	82.69

The mechanical tests of the TRIP steel wires were carried out on a ZWICK/Z100 testing machine. Figures 1-6 illustrate the variation in the ultimate tensile strength R_m, the yield strength $R_{0.2}$ and the $R_{0.2}/R_m$ ratio as a function of the total reduction in area for wires drawn with small and large partial reductions, respectively, and for two drawing speeds: v=1.11 m/s and v=0.23 m/s.

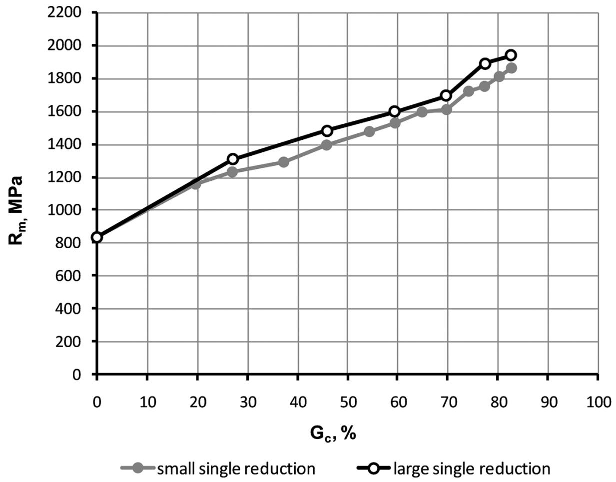

Fig. 1. Variation in the ultimate tensile strength R_m of TRIP steel wires drawn with small and large partial reductions, respectively, at a drawing speed of 1.11 m/s, as a function of the total reduction in area [10]

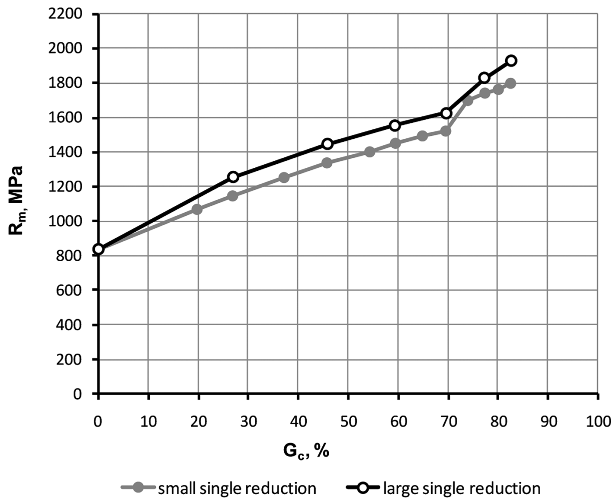

Fig. 2. Variation in the ultimate tensile strength R_m of TRIP steel wires drawn with small and large partial reductions, respectively, at a drawing speed of 0.23 m/s, as a function of the total reduction in area [10]

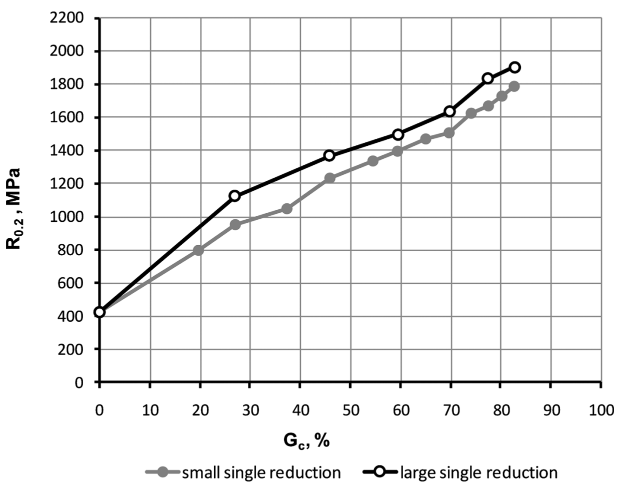

Fig. 3. Variation in the yield strength $R_{0.2}$ of TRIP steel wires drawn with small and large partial reductions, respectively, at a drawing speed of 1.11 m/s, as a function of the total reduction in area [10]

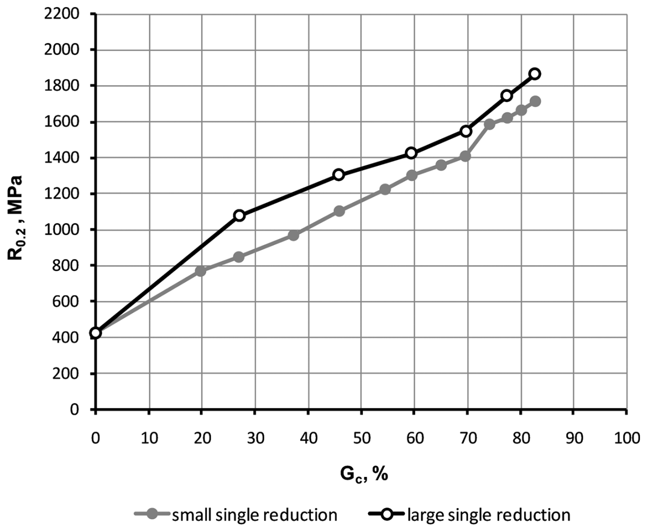

Fig. 4. Variation in the yield strength $R_{0.2}$ of TRIP steel wires drawn with small and large partial reductions, respectively, at a drawing speed of 0.23 m/s, as a function of the total reduction in area [10]

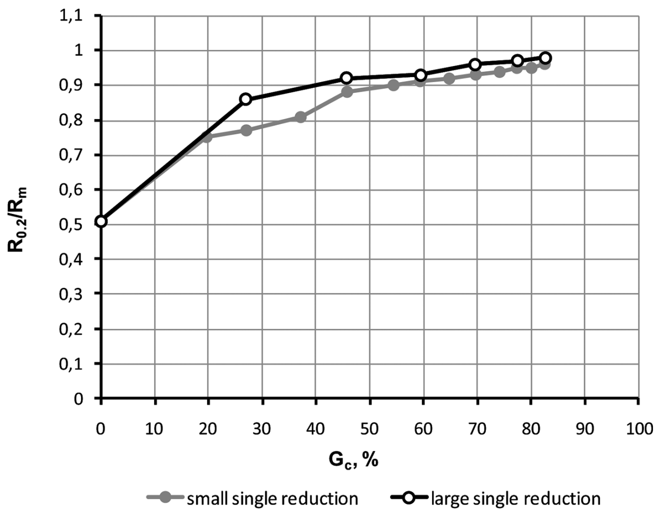

Fig. 5. Variation in the $R_{0.2}/R_m$ ratio for TRIP steel wires drawn with small and large partial reductions, respectively, at a drawing speed of 1.11 m/s, as a function of the total reduction in area [10]

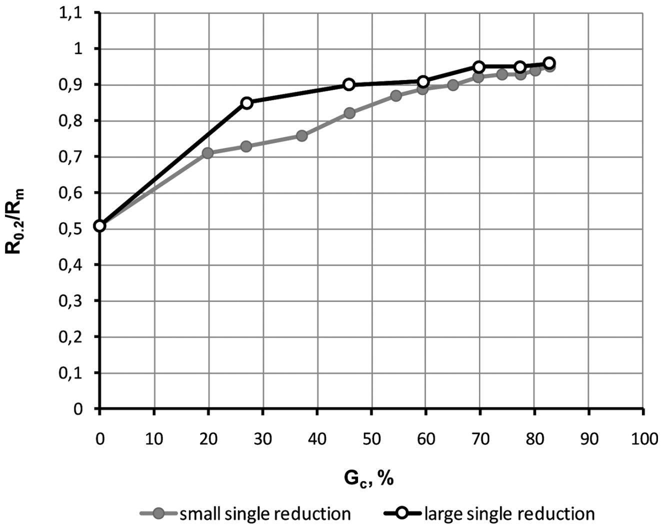

Fig. 6. Variation in the $R_{0.2}/R_m$ ratio for TRIP steel wires drawn with small and large partial reductions, respectively, at a drawing speed of 0.23 m/s, as a function of the total reduction in area [10]

The analysis of the ultimate tensile strength (R_m) variation results allows one to find that, regardless of the speed at which the drawing process was conducted, the increase in the value of R_m after respective deformation degrees was greater for the process run with large partial reductions (Figs. 1, 2). So, for example, after exceeding a total reduction of about 30%, the ultimate tensile strength for the process conducted with large partial reductions was by approx. 6% higher compared to the process of drawing with small partial reductions.

We can notice that at the drawing speed equal to 0.23 m/s, the differences in R_m values for the process conducted with small partial reductions, as against the process run with large partial reductions, amount to approx. 10% for G_c =27%, which means that they are by about 5% higher than for drawing with the drawing speed equal to 1,11 m/s. This may be caused by the greater effect of the retained martensite-to martensite transformation on the material hardening, being largely dependent on the strain rate.

When analysing the values of the yield strength $R_{0.2}$ (Figs. 3, 4) it was found that, similarly as for the ultimate tensile strength, these values were higher for the process conducted with large partial reductions. For a total reduction of about 30%, the differences in $R_{0.2}$ values between the small partial reduction drawing process and the large partial reduction process reached 15%. As the deformation increased, this value decreased, and for final wires with a total reduction of 82.69% it was 5%.

In order to establish the susceptibility of the drawn wires to plastic deformations, the $R_{0.2}/R_m$ ratio, which defines the so called ”plasticity reserve” of material being deformed, was analyzed (Figs. 5, 6). The lower this ratio, the more susceptible to plastic deformation the material is.

The $R_{0.2}/R_m$ ratio values were higher for the large partial reduction drawing process. It was found that for the drawing process conducted with small partial reductions at a lower drawing speed, the $R_{0.2}/R_m$ ratio value significantly increased after exceeding a total reduction of about 50%, whereas for the large partial reduction drawing process, the plasticity decreased already from a total reduction value of approx. 30% (Fig. 6).

2. Analysis of the effect of drawing speed on the mechanical properties of TRIP steel wires.

For examining the influence of drawing speed on the mechanical properties of wires, Figures 7-12 show the variation in the values of ultimate tensile strength, R_m; yield strength, $R_{0.2}$; and the ratio $R_{0.2}/R_m$ as a function of the total reduction in area for wires drawn at varying drawing speeds.

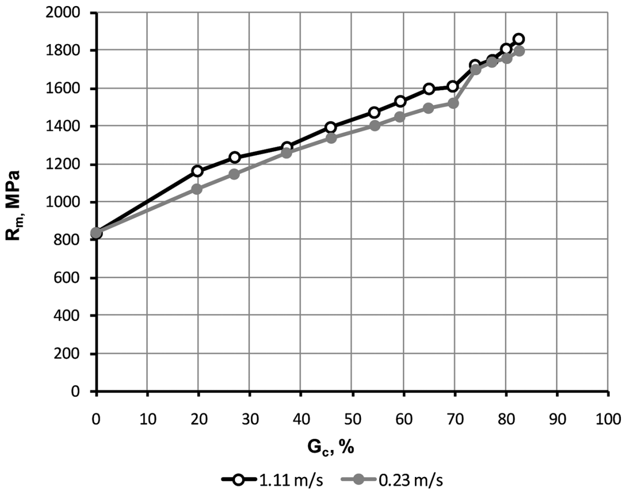

Fig. 7. Variation in the R_m tensile strength of TRIP steel wires drawn with small partial reductions and at a drawing speed of v_1 =1.11 m/s and v_2 =0.23 m/s, respectively, as a function of the total reduction in area [10]

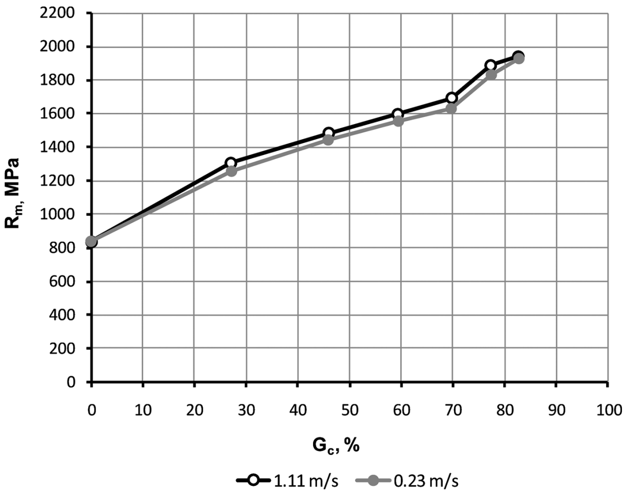

Fig. 8. Variation in the R_m tensile strength of TRIP steel wires drawn with large partial reductions and at a drawing speed of v_1 =1.11 m/s and v_2 =0.23 m/s, respectively, as a function of the total reduction in area [10]

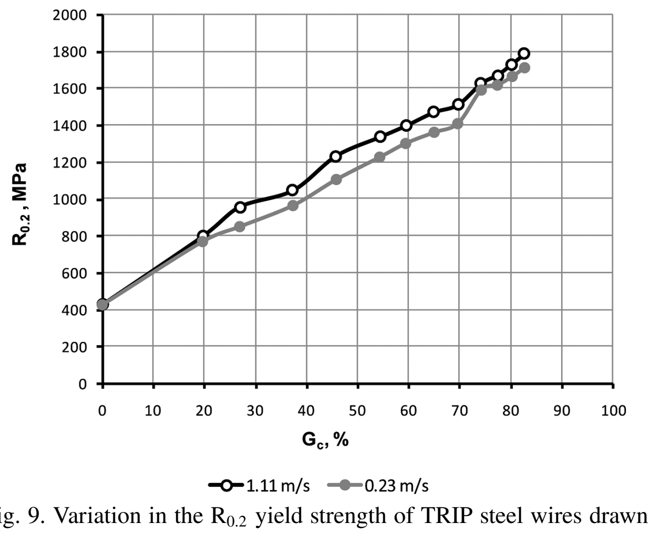

Fig. 9. Variation in the $R_{0.2}$ yield strength of TRIP steel wires drawn with small partial reductions and at a drawing speed of v_1 =1.11 m/s and v_2 =0.23 m/s, respectively, as a function of the total reduction in area [10]

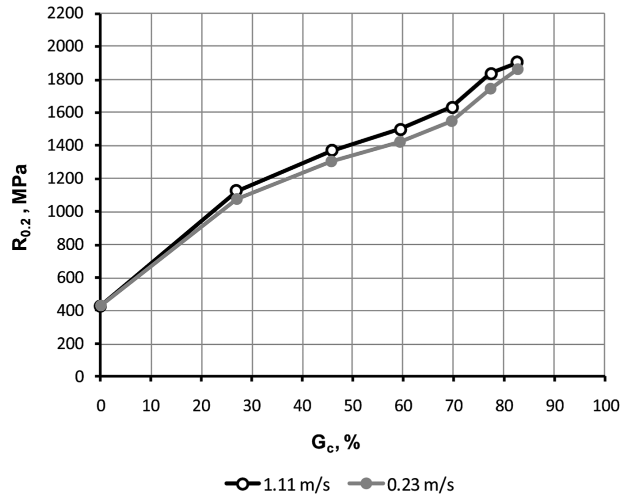

Fig. 10. Variation in the $R_{0.2}$ yield strength of TRIP steel wires drawn with large partial reductions and at a drawing speed of v_1 =1.11 m/s and v_2 =0.23 m/s, respectively, as a function of the total reduction in area [10]

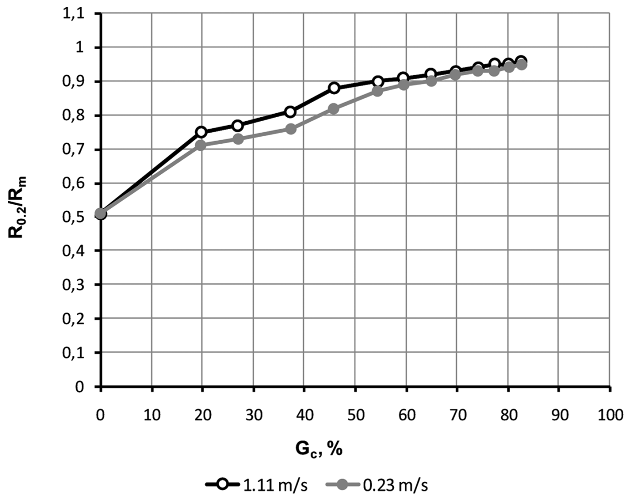

Fig. 11. Variation in the $R_{0.,2}/R_m$ ratio of TRIP steel wires drawn with small partial reductions and at a drawing speed of v_1 =1.11 m/s and v_2 =0.23 m/s, respectively, as a function of the total reduction in area [10]

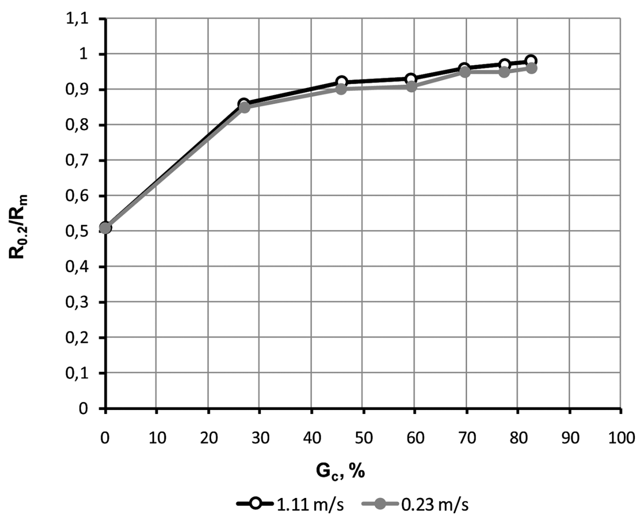

Fig. 12. Variation in the $R_{0.,2}/R_m$ ratio of TRIP steel wires drawn with large partial reductions and at a drawing speed of v_1 =1.11 m/s and v_2 =0.23 m/s, respectively, as a function of the total reduction in area [10]

By analyzing the presented results it can be found that the increase in drawing speed causes an enhancement in the mechanical properties of the drawn wires by approx. 5%. The values of R_m and $R_{0.2}$ were higher for wires drawn at a higher drawing speed for both small and large partial reductions. It was found that for the drawing process conducted with small partial reductions, after exceeding a total reduction of approx. 70% the differences in the values of the $R_{0.2}/R_m$ ratio for both drawing speeds had decreased to approx. 2%.

The tests carried out showed that for the drawing process with large partial reductions a rapid decrease in the plasticity reserve occurred within the total reduction range from 0 to 25% (Figs. 5, 6 and 12). This might be caused by the effect of material hardening formed in the material due to the intensive transformation of retained austenite to martensite, which becomes quickly depleted in processes conducted at a high strain rate and strain intensity.

The test results for the process of drawing with small partial reductions indicate a slower decrease in the plasticity reserve and, as a consequence, slower material hardening with increasing deformation.

The presented results confirm the presumptions that the partial reduction magnitude has a significant influence on the intensity of transformation of retained austenite to martensite. They also indicate an indisputable effect of strain rate on this transformation. For a drawing process conducted at a speed of 1.11 m/s (with small partial reductions) the material intensively hardens up to a total reduction value of approx. 45%; whereas, for a drawing process run at a speed of 0.23 m/s the intensity of hardening is observed up to a total reduction value of 60% (Figs. 5, 6 and 11).

The behaviour of $R_{0.2}/R_m$ ratio variations for large partial reductions, irrespective of the drawing speed, is similar; they only differ in the level of values, which are smaller for v_c =0.23m/s. However, no differences in the behaviour of the curves, which would be so significant as in the case of the drawing process conducted with small partial reductions, are found.

3. Comparing the properties of TRIP steel wires with those of wires made of a ferritic-pearlitic structure steel with identical chemical composition.

To determine the effect of structure on the wire properties, wire rod and wires made of the same material (with identical chemical composition) as the one of which the TRIP steel wires were made, except for having a ferritic-pearlitic structure, that is a typical structure that is obtained after hot wire rod rolling process, were put to mechanical tests. The wire rod of this structure is used directly (with no heat treatment) for the drawing process.

The ferritic-pearlitic structure wire rod was subjected to the process of drawing with the same process parameters (i.e. partial reductions - variant 1, v_c =1.11 m/s) as for the TRIP steel wire rod.

To compare the mechanical properties of wires of the same steel with different structures, graphs (Figs. 13-15) have been plotted, which represent the variations of R_m, $R_{0.2}$ and $R_{0.2}/R_m$ as a function of the total reduction in area.

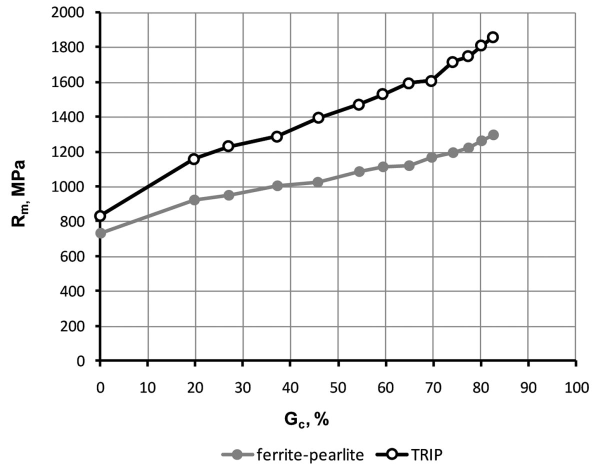

Fig. 13. Variation of the R_m tensile strength of wires made of TRIP steel and wires made of ferritic-pearlitic structure steel not heat treated (without the TRIP effect), drawn with small partial reductions and at a drawing speed of v=1.11 m/s, as a function of the total reduction in area [10]

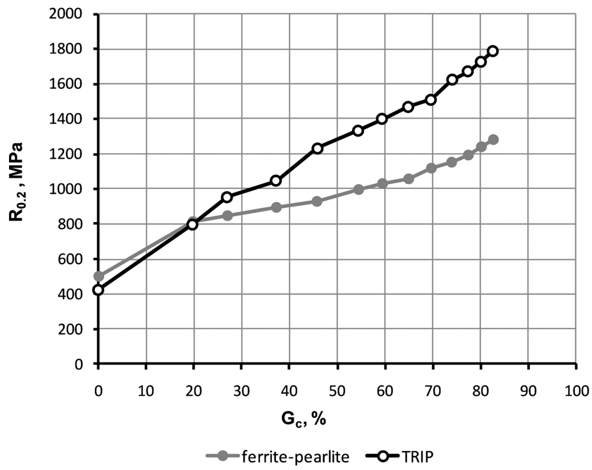

Fig. 14. Variation of the $R_{0.2}$ yield strength of wires made of TRIP steel and wires made of ferritic-pearlitic structure steel not heat treated (without the TRIP effect), drawn with small partial reductions and at a drawing speed of v=1.11 m/s, as a function of the total reduction in area [10]

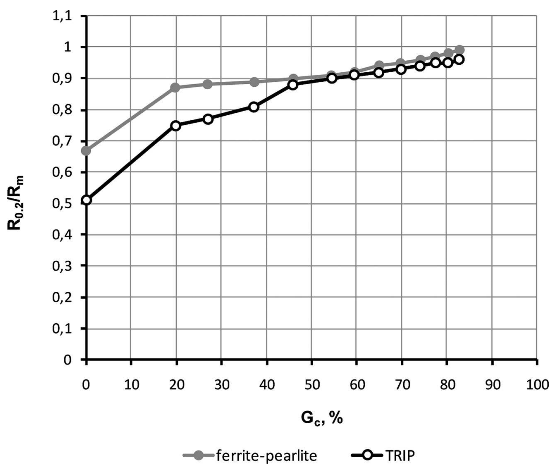

Fig. 15. Variation of the $R_{0.2}/R_m$ ratio of wires made of TRIP steel and wires made of ferritic-pearlitic structure steel not heat treated (without the TRIP effect), drawn with small partial reductions and at a drawing speed of v=1.11 m/s, as a function of the total reduction in area [10]

The analysis of the tensile strength variation results for wires of TRIP structure steel and of ferritic-pearlitic structure steel has found that the heat treatment carried out with the aim of obtaining retained austenite in the structure of the wire rod has a significant effect of increasing the R_m of the drawn wires.

The wire rod heat treated prior to the drawing process had an R_m value higher by approx. 100 MPa compared to the wire rod of identical chemical composition, but not heat treated.

An increase in the differences between the R_m values up to a value of approx. 31% for final 2.60 mm-diameter wires (a total reduction of 82.69%) can also be found.

A similar relationship is observed for variations in the yield strength, $R_{0.2}$. The TRIP steel wires had higher yield strength values; they also underwent slower hardening up to a G_c value of approx. 50%. After exceeding the total reduction value of about 50%, the $R_{o.2}/R_m$ ratio of the TRIP steel wires was nearly the same as that of that of the ferritic-pearlitic structure steel wires. This might have resulted from the depletion of retained austenite in the TRIP steel wire structure and the hardening of the material also due to the formation of the hard martensitic phase.

3. Conclusions

1. It can be notice that with the increase in the total reduction value, the differences between the hardening of the material and its plasticity decrease, which is closely related to the depletion of the retained austenite in the TRIP steel structure, until it is totally exhausted at a total reduction of approx. 60%, for which the $R_{0.2}/R_m$ ratio is about 0.90.
2. Above a certain partial reduction value the effect of drawing speed on the decrease of material plasticity become insignificant.
3. After the retained austenite has been depleted in the structure due to its transformation to martensite, the differences in the values of the $R_{0.2}/R_m$ ratio for large and small partial reductions, as well as different drawing speeds, are little significant, being around 3%.
4. It has been found that there is a potential for controlling and forecasting the drop in the plasticity of TRIP steel wire within a certain range of partial reductions and drawing speeds, e.g. for v_c =1.11 m/s - $R_{0.2}/R_m$ =0.92 (with large partial reductions), and for v_c =0.23 m/s - $R_{0.2}/R_m$ =0.82 (for small partial reductions).
5. It was found that heat treatment carried out to produce a TRIP-type multi-phase structure in the wire rod being the starting material for the drawing process enabled considerably higher mechanical properties to be achieved in the drawn wire compared to wires drawn from not heat treated wire rod with a typical ferritic-pearlitic structure.
6. The mechanical strength values of TRIP steel wires are comparable to properties of wires made from high-carbon steel.

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Received: 15 December 2012.