Hutnické listy č. 2/2017, roč. LXX
ISSN 0018-8069

Influence of Casting Speed on Solidification of Continuously Cast Round Steel Billets

Vliv licí rychlosti na tuhnutí kruhových plynule odlévaných ocelových předlitků

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Numerické modelování představuje užitečný nástroj k získání informací týkajících se chování oceli v různých fázích výroby. Metoda numerického modelování hraje nezastupitelnou roli zvláště v metalurgických podmínkách, ve kterých lze jen obtížně získat informace o způsobu tuhnutí kovu. Předkládaná práce představuje základní postup experimentálního studia využívajícího numerické modelování v komerčním simulačním software ProCAST, které je používáno k verifikaci technologie plynulého odlévání. Modelové studium tuhnutí bylo mimo jiné zaměřeno na predikci vzniku středové porozity v plynule litých ocelových předlitcích. Ke vzniku středové porozity dochází na konci metalurgické délky, v místě, kde se stýkají protilehlé fronty tuhnutí a svírají úhel ω. Tvorba středové porozity tedy úzce souvisí s průběhem tuhnutí plynule litých předlitků. Úhel ω se zvětšuje se zkracující se metalurgickou délkou, což se projevuje snížením výskytu porozity. Charakter tuhnutí předlitku lze ovlivnit změnou licí rychlosti. Obvykle je v provozu změna licí rychlosti doprovázena i změnou chlazení jak v primární, tak sekundární zóně. Aby však bylo možné posoudit vliv technologického parametru na změnu sledovaných kvalitativních ukazatelů předlitku, byla během numerického modelování pozměněna pouze licí rychlost při zachování intenzity chlazení. Pozornost byla proto věnována převážně vlivům změny licí rychlosti na metalurgickou délku, s kterou souvisí vznik porozity, ale také na teplotní pole a tloušťku utuhlé povrchové kůry pod krystalizátorem. V souladu s literárními poznatky i výsledky modelování bylo potvrzeno, že s klesající licí rychlostí se zvyšuje podíl utuhlé frakce v předlitku. Zvýšení podílu utuhlé frakce bylo způsobeno prodloužením doby, kterou předlitek strávil v chladicích zónách. Uvedená skutečnost se pozitivně projevila především na zvětšení tloušťky povrchové kůry a zkrácení metalurgické délky. Na základě výsledků metalurgické délky lze usuzovat, že při snížení licí rychlosti dojde ke snížení výskytu středové porozity.

***Klíčová slova**: ocel; numerické modelování; plynulé odlévání; kruhové předlitky; středová porozita*

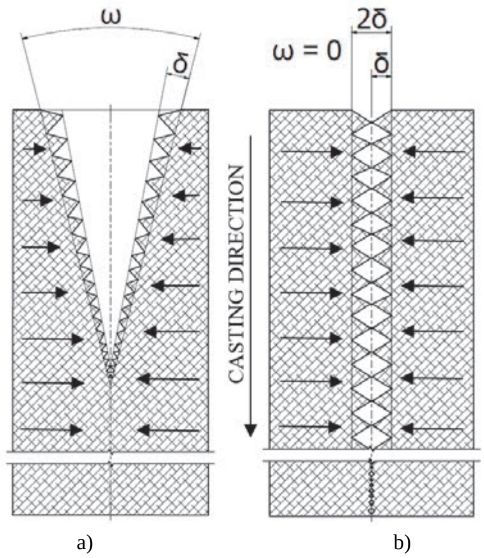
The aim of this paper is the study of solidification of continuously cast round steel billets, with focus on the centerline porosity formation. This work represents the basic procedure of experimental study using numerical modelling in commercial simulation software ProCAST, which was used to verify the technology of continuous casting of round steel billets. The attention was paid especially to prediction of solidification of continuously cast steel billets and centerline porosity formation related to casting speed. The centerline porosity formation is closely related to the solidification process, especially to the angle formed between the opposite solidification fronts. The angle formed between the solidification fronts increases with shortening of metallurgical length due to reduction of the casting speed. Reduction of the casting speed has therefore possible influence on minimization of the centerline porosity.

***Key words**: steel; numerical modelling; continuous casting; round billets; centerline porosity*

During continuous casting of steel, forming of several internal defects can occur. The cause of these defects can be inappropriate casting conditions, e.g. regulation of casting speed according to casting temperature or incorrectly adjusted secondary cooling, which leads to incorrect solidification of the billet. In the field of continuous casting, phase transformations during which a liquid phase becomes a solid phase, have a significant importance. This phase transformation - solidification – is characterized by volume change and latent heat production. Solidification has significant importance also on the primary structure and related final mechanical and thermodynamic properties. Steel, as an alloy consisting of Fe, C and other elements, solidifies in a certain temperature range, characterized by distance between the liquidus and solidus temperature. Solidification in the temperature range results in formation of a two-phase region (mushy zone), which contains liquid and solid phase. [1, 2, 3] During solidification of continuously cast billets the following may coexist:

- Liquid region – its width is constantly decreasing
- Mushy zone – its width depends on the solidification temperature range
- Solidified region – its width is constantly increasing

At the end of metallurgical length (at the end of the liquid core), where the mushy zone is located, due to damming of liquid core, thereby forming an enclosed volume of liquid metal, a centerline porosity formation can occur. After solidification, because of shrinkage of steel, the enclosed volume becomes a cavity. Dam creation largely depends on the angle ω, which forms opposite solidification fronts progressing from the surface of billet to its center. Risk of the centerline porosity formation decreases with the increasing angle ω (Fig. 1a). Increase of the angle ω occurs when metallurgical length (and hence the mushy zone) shortens. Conversely, when the metallurgical length extends, the angle ω decreases (Fig. 1b) and the risk of the porosity formation increases [3]. The centerline porosity creation closely depends on the solidification process of continuously cast billet and on the metallurgical length [1, 4].



a) b)

Fig. 1 Solidification conditions a) for minimization of centerline porosity formation; b) supporting centerline porosity formation [3]

Obr. 1 Podmínky pro a) tuhnutí zdravého předlitku; b) tuhnutí předlitku se středovou porozitou [3]

In order to prevent the centerline porosity, it is necessary to determine specific conditions of its formation. For this purpose, effective tool, which avoids the need of expensive and time-consuming plant trials, represents the numerical modelling. Under the metallurgical conditions, it is difficult to obtain information about solidification of continuously cast billets. At this point comes the numerical modelling, which plays an important role, especially in metallurgical processes. Numerical modelling requires a detailed knowledge about natural processes, e. g. flow, heat transfer, momentum transfer etc. Regarding the temperature field, it is possible to use analytical or numerical methods to solve this problem. [1, 4, 5, 6] Due to the fact that analytical methods lead to complex system of equations, they have only limited use for problems with complex boundary conditions. Numerical methods are based on repeating of simple algebraic operations and it is preferable to use them in combination with complex boundary conditions [7].

This paper has been written in connection with numerical research realized under the conditions of the Department of Metallurgy and Foundry and Regional Materials Science and Technology Centre (RMSTC) at the VŠB-TU Ostrava. The aim of numerical modelling was the study of solidification of continuously cast round steel billets. Attention was paid to the influence of casting speed on the temperature field, solidified shell thickness and metallurgical length. In relation with to the metallurgical length, the centerline porosity dependence on the casting speed was also investigated.

1. Identification of input parameters

Generally speaking, numerical solution of each task is divided into three stages [8]:

- Pre-processing – it includes the geometry modelling and process of generation of the computational mesh, and definition of calculation;
- Processing – it involves the computation in the solver;
- Post-processing: it focuses on evaluation of the results.

For obtaining a default version of the numerical model of solidification of the steel billets in accordance with the real conditions of solidification as accurately as possible, it was important to define correctly the parameters of calculation. The necessary parameters include the following:

- thermodynamic properties of steel (i.e. liquidus and solidus temperatures, thermal conductivity, density, part of solid phase etc.);
- boundary conditions:
  - casting temperature,
  - casting speed,
  - level of steel in mould,
  - difference of temperature of cooling water between the mould inlet and outlet,
  - heat flux along the mould,
  - heat transfer coefficient along the secondary cooling zone,
  - ambient temperature,
- operating conditions (gravity, ambient pressure);
- criteria of convergence, the so-called RUN PARAMETERS or Simulation parameters.

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ISSN 0018-8069

2. Summary of suggested variants for verification

Three variants of solidification of continuously cast round steel billets were simulated. The first variant A introduced the case when the casting speed was set to v - 0.1 m·min^{-1} and the casting temperature t_L + 38 °C was used, as it is shown in Tab. 1. The second variant B represented a case, in which the casting speed was increased to v m·min^{-1} against the variant A. In the last third variant C, the casting speed was further increased to v + 0.1 m·min^{-1} against the variant A.

Tab. 1 The list of simulated variants
Tab. 1 Přehled simulovaných variant

Variant	Casting Temperature	Casting Speed
	(°C)	(m·min^{-1})
A	t_L + 38	v – 0.1
B	t_L + 38	v
C	t_L + 38	v + 0.1

3. Geometry creation

For the purposes of numerical model, a billet geometry was created. Numerical simulations were carried out in one symmetrical half of the billet, which included mould section, whole radial part of the billet and 5 m from the straight end part of the billet. Total length of the billet geometry was 22 m. With consideration of computational possibilities of ProCAST, a simplification of billet geometry was necessary. Computational method and mesh creation also required simplification of the mould taper to a uniform diameter. Due to the fact that flow calculation was neglected, submerged entry nozzle reaching under a molten steel surface in the mould was also neglected. Computational mesh (Fig. 2) was created from hexa- and wedge elements, the finite number of which reached approx. 400 000. Due to reduction of computational time only one symmetrical half of the billet geometry was used, as it was already mentioned.

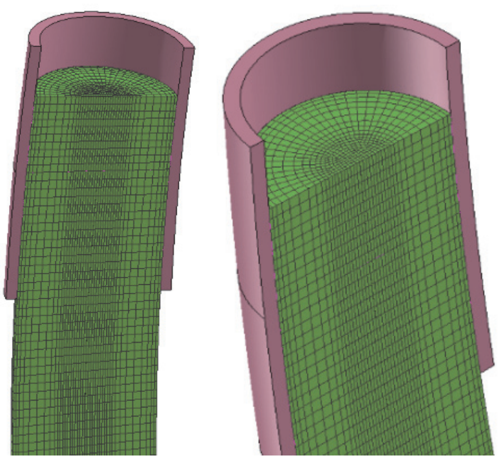

Fig. 2 Computational mesh – detailed view
Obr. 2 Detailní pohled na výpočetní síť předlitku

4. Definition of numerical model

Correct setting of numerical model requires definition of initial and boundary conditions. Initial and boundary conditions of numerical model of continuous casting includes direction of gravity, ambient temperature and pressure, casting speed and temperature, heat losses from billet surface in the mould and in the secondary cooling zone. The main mechanism of heat transfer from billet is conduction. However, convection and radiation play an important role in the field of boundary conditions, in particular, convection and radiation.

The boundary conditions, such as casting speed and casting temperature, were defined according to the plant data. The ambient temperature was 298 K. The level of the steel in the mould was 80 % from the height of the mould. [9] The temperature difference between the inlet and outlet of cooling water in the mould was 12 K. The gravity was 9.81 m·s^{-2}. The standard pressure was considered to be 101 325 Pa.

Also, thermodynamic parameters play an important role, especially in the processing phase. These parameters are substitute to Fourier-Kirchhoff solidification equations, computed for all mesh elements and they thus may affect the quality of the simulation results [10]. Based on chemical composition (see Tab. 2), thermodynamic properties of steel were computed using the integrated thermodynamic database CompuTherm, which is a part of ProCAST software [11, 12].

Tab. 2 Chemical composition of steel grade (wt. %) [13]
Tab. 2 Chemické složení oceli (hm. %) [13]

	C	Si	Mn	P	S	Cr	Mo
min	0.30	-	0.60	-	-	0.90	0.15
max	0.37	0.40	0.90	0.035	0.035	1.20	0.30

In order to capture the influence of casting speed, the same casting temperature and intensity of heat losses for all three variants were set. Similarly, it was made also in the case of other technological parameters, such as meniscus position, cooling water flow and temperature. Accordingly, during simulations only casting speed was changed and all the other parameters were considered to be constant. Surface temperatures were used for an assessment of approximate heat transfer coefficients.

Heat transfer in the primary and secondary zones were defined through the boundary condition *heat*, which allowed definition of heat transfer between the domain surface and ambient atmosphere. To this boundary condition, it was possible to assign an appropriate heat transfer coefficient between the domain surface and ambient atmosphere and ambient temperature, which influence conditions of surface cooling.

In the primary zone a casting powder and a gas gap were located between the mould and billet surface and they had a significant impact on the heat transfer coefficients values along the height of the billet. Heat transfer through casting powder and gas gap was defined by *heat flux* user function during setting of heat boundary condition. Heat transfer in the secondary zone was set similarly by using *HTC* user function.

For simulation, the travelling boundary algorithm was used. Numerical solution of the mathematical model of solidification of the continuously cast steel strand was performed using the finite element method.

5. Results and discussion

Numerical results were evaluated in post-processor of the ProCAST software – Visual Viewer. Especially, temperature fields on the billet surface were evaluated using the temperature profiles and graphical outputs. Also, the casting shell thicknesses at the end of the mould and metallurgical lengths were compared.

5.1 Temperature field

Visualization of the billet surface temperature field of all variants is shown in Fig. 3.

Fig. 3 Billets temperature field (from the left to right A, B, C)
Obr. 3 Teplotní pole předlitků (zleva doprava A, B, C)

Fig. 4 shows the detailed view of temperature field in the mould region Fig. 5 shows the billet surface temperature profiles in dependence on the casting time (which represents the casting speed) of all three simulated variants. As it can be seen, with decrease of the casting speed, the billet surface temperature decreases. This phenomenon was caused by the fact that with the decreasing casting speed, the time that billet spent in the cooling zones was increased. Due to longer time spent in the cooling zones, more heat from the billet was dissipated and resulted in lower surface temperature.

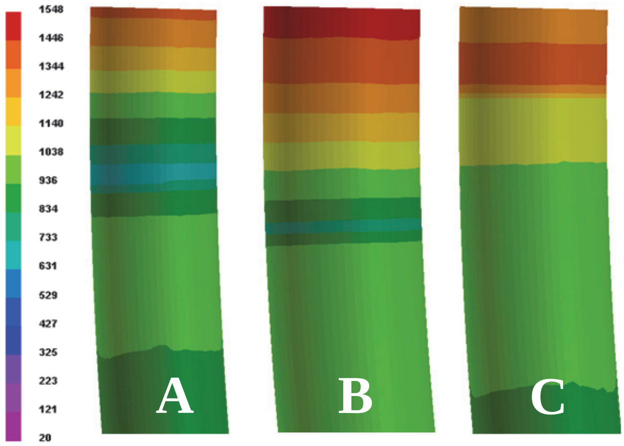

Fig. 4 Temperature field of simulated variants in the mould region
Obr. 4 Teplotní pole simulovaných variant v oblasti krystalizátoru

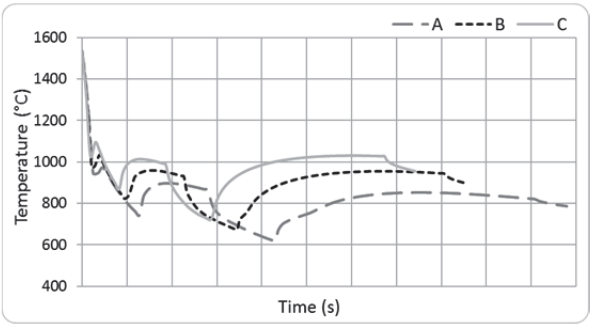

Fig. 5 Computed billet surface temperature profiles
Obr. 5 Vypočtené povrchové teplotní křivky předlitků

5.2 Shell thickness

With the use results of part of solid phase, the shell thickness was evaluated. The shell thickness was measured at the end of the mould. The position of measurement is indicated by dashed line in Fig. 6. Dependence of the shell thickness on the casting speed is represented in Fig. 7. It was manifested that when the time the billet spent under cooling increased (it means decrease of the casting speed), it resulted in larger amount of fraction solid. With the decrease of the casting speed, the shell thickness increased.

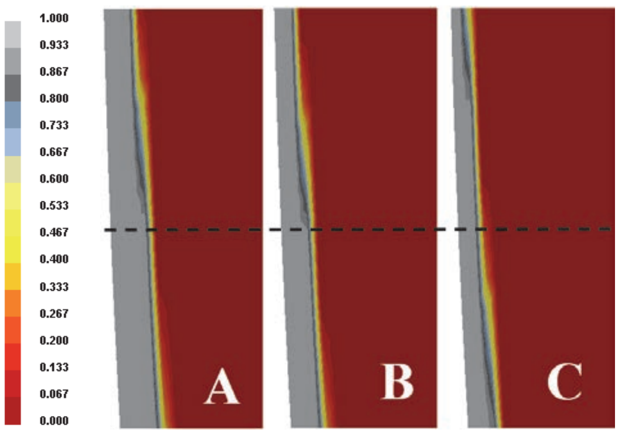

Fig. 6 Results of part of solid phase – Shell Thickness (measurement position is indicated by dashed line)
Obr. 6 Výsledky Fraction Solid – Tloušťka licí kůry (pozice měření je vyznačena čárkovaně)

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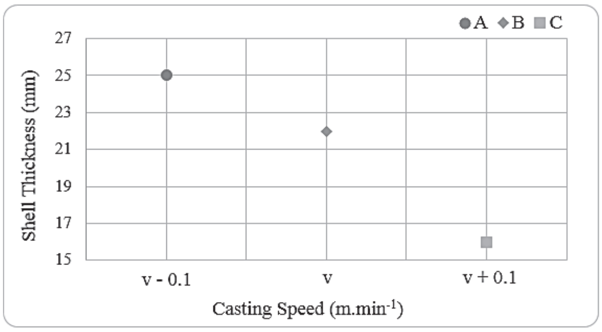

Fig. 7 Shell thickness dependence on the casting speed
Obr. 7 Tloušťka licí kůry v závislosti na licí rychlosti

In the past, several equations for calculation of the shell thickness were derived. Shell thickness was frequently calculated using the equation (1), which was the most general of the mentioned ones [14].

$$d = 22{,}86.\sqrt{t} - 3{,}05 \quad (1)$$

where t - time (min).

The equation (2) includes also solidification constant *k*. The solidification constant depends on cross-section of the billet, superheating of steel, chemical composition and cooling rate [3, 14]. The value of the solidification constant was determined by interpolation from the temperature dependence.

$$d = k.\sqrt{t} \quad (2)$$

where k - solidification constant ($mm \cdot min^{-1/2}$),
t - time (min).

The equation (3) takes into account variation of the casting speed in dependence on the steel grade, mould dimensions and water flow rate in the mould [14]. This equation was primarily designed for calculation of slab shell thickness. For the purposes of this paper, instead of the product of mould walls dimensions (a·b), which express the cross-section of the slab, the cross-section of the round billet was used.

$$d = \frac{\rho_W \cdot c_W \cdot G \cdot \Delta t}{\rho_S \cdot L \cdot l \cdot v + v \cdot a \cdot b \cdot \rho_S \cdot \Delta t \cdot c_S} \quad (3)$$

where ρ_w - water density ($kg \cdot m^{-3}$),
c_w - water specific heat ($J \cdot kg^{-1} \cdot K^{-1}$),
G - mould water flow rate ($m^3 \cdot s^{-1}$),
Δt - difference between temperature at the inlet and outlet of the mould (K),
ρ_s - steel density ($kg \cdot m^{-3}$),
L - latent heat of solidification ($J \cdot kg^{-1}$),
l - diameter of the billet (m),
v - casting speed ($m \cdot s^{-1}$),
$a \cdot b$ - mould cross-section (m^2),
c_s - steel specific heat ($J \cdot kg^{-1} \cdot K^{-1}$).

Comparison of the calculated values according to the equations (1) – (3) and the results of numerical model (NM) of shell thickness were carried out. The results are shown in Fig. 8. It could be said that the best match between the measured and computed values of the shell thickness were achieved by the results calculated by the equation (1). However, even in this case, deviation of the calculated values differed by up to 4.3 mm from the results of numerical model. The most significant deviation between the results of numerical model and computation show the values calculated by the equation (3). Discrepancies between the results of numerical model and the calculated values could be related to the fact that the equation (3) was primarily derived for calculation of slabs shell thickness. If the area of rectangular mould (a·b) was replaced by the area of circle mould, the computed shell thickness was probably over-dimensioned.

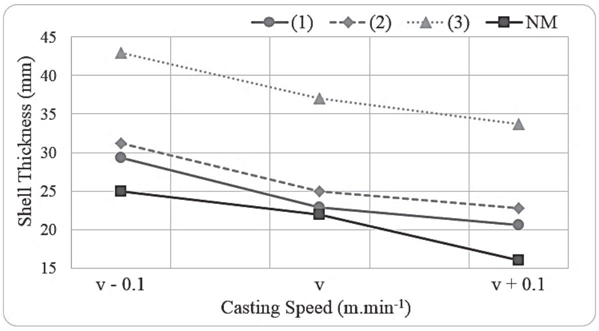

Fig. 8 Comparison of calculated and measured values of the shell thickness
Obr. 8 Srovnání vypočtených a naměřených hodnot tloušťky licí kůry

5.3 Metallurgical length

Fig. 9 represents illustration of metallurgical length results, which were obtained using part of solid phase. In the case of metallurgical length also influence of the casting speed or of the time spent in cooling zones has been reflected. With the decrease of the casting speed, the time of billet spent under cooling increased, which resulted in larger amount of part of solid phase and shorter metallurgical length (see Fig. 10).

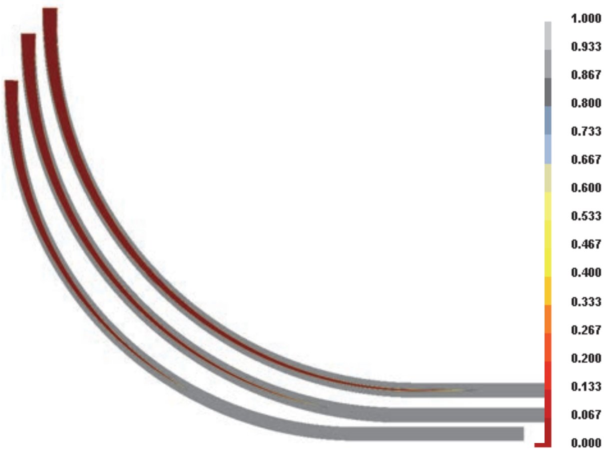

Fig. 9 Billets metallurgical length (from bottom A, B, C)
Obr. 9 Metalurgická délka předlitků (od spodu A, B, C)

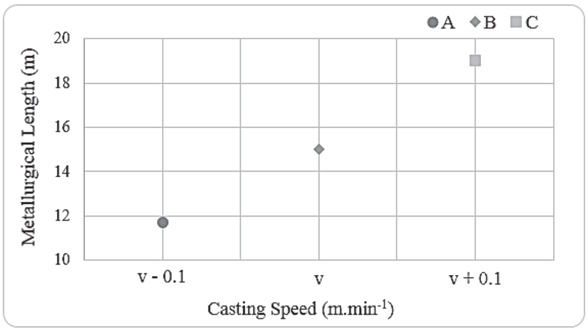

Fig. 10 Dependence of metallurgical length on the casting speed
Obr. 10 Závislost metalurgické délky na licí rychlosti

Conclusions

Numerical simulations of solidification of continuously cast round steel billets were carried out. During simulations, temperature field, metallurgical length and shell thickness were computed. It was found out, that with the decrease of the casting speed:

- the surface temperature of billet decreased;
- the shell thickness increased;
- the metallurgical length shortened.

The mentioned conclusions are in good agreement with the literature knowledge. In terms of minimizing formation of the centerline porosity in continuously cast round steel billets, casting with lower casting speed could be recommended. As it was already explained in the introduction, the centerline porosity formation is related to the metallurgical length (and therefore to the casting speed) of continuously cast billets. Thus, decrease of probability of billet centerline porosity formation with the decrease of casting speed can be expected. In accordance with this results it can be said that in the case of variant A (from the above variants) the occurrence of the centerline porosity is the least likely. Further detailed analysis of solidification of the continuously cast round steel billets will be focused on this issue.

Acknowledgement

The work was created with the support of projects of the Student Grant Competition Nos. SP2017/57 and SP2017/58.

This paper was created within the project No. LO1203 “Regional Materials Science and Technology Center – “Feasibility Program“ funded by the Ministry of Education, Youth and Sports of the Czech Republic.

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Výrazné oživení přišlo na podzim

Focus Rostfrei *02.01.2017*

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