As a rule, hot-worked tubes are produced by hot rolling using various tube-rolling units incorporating a continuous mill, a pilger mill, an automatic mill or a three-roll reeling mill [1–3]. For reliable operation, these tubes must meet all requirements of regulatory documents including quality of the outer and inner surfaces. Piercing of a preheated initial tube billet [3–5] is one of the main operations in the process flowchart of manufacturing hot-rolled tubes on any of the above units. As is known, violation or imperfections of the process of billet heating before piercing lead to formation of unacceptable defects of a tube-rolling origin [6–8]. To exclude formation of defects in shells and, accordingly, in the finished tubes, metal of the tube billet should have a sufficiently high plasticity and low resistance to deformation which, taken as a whole, determine processing plasticity of the billet metal [9–12].

Recently, the enterprises producing hot-worked tubes are beginning to use nonworked continuously cast billets (CCBs) along with conventional worked tube billets obtained from stationary or continuously cast ingots. The study results will also serve as a basis for improving the CCBs manufacture technology at MZ Dniprostal LLC in order to obtain a macrocrystalline structure of the billet metal which will ensure a satisfactory level of processing plasticity as well as a more uniform distribution of plastic properties over the CCBs section.

Key words: nondeformed continuously cast tube billet, macrocrystalline structure, columnar crystals, equiaxial mis-oriented crystals, processing plasticity, hot twisting tests, number of twists to failure, twisting force.
Interpipe Niko Tube LLC is one of such enterprises having the ability to use CCBs manufactured by MZ Dniprostal LLC which, like Interpipe Niko Tube LLC, is a part of the Interpipe Corporation.

However, temperatures to which the billets are heated before hot rolling experimentally established for worked tube billets and tested for many years at Interpipe Niko Tube are not fully suitable for the CCBs remarkable for their dendritic chemical and structural heterogeneity [16–18]. The use of conditions of CCB heating before piercing adapted only for worked billets can lead to formation of defects (including hidden ones) of varying degrees of roughness of the finished tube surface which become apparent only during the tube operation.

To determine an optimal temperature range of heating before piercing the non-worked continuously cast tube billets of carbon steel grades which ensures maximum plasticity of the billet metal under conditions of a complex stressed state during hot deformation and, accordingly, reduce likelihood of formation of defects on the tube surface, it is necessary to conduct a study of processing plasticity of such billet metal.

The study object included 210 mm dia. CCBs made of 10U and 20U steel grades (according to MZ Dniprostal LLC Grade Nomenclature and 150 mm dia. CCBs of ‘20’ boiler steel grade (according to Technical Specification

\[ \text{Dependence of average values of the number of twists } n \text{ (a) and deformation force } P_{cr} \text{ (b) on test temperature for the CCBs made of 10U steel grade} \]

\[ \text{Dependence of average values of the twist number } n \text{ (a) and deformation force } P_{cr} \text{ (b) on test temperature for the CCBs made of ‘20’ steel grade} \]
that of the billets made of the above two steel grades by presence of an asymmetrically located zone of equiaxed crystals (up to 30% area) and a zone of transcrystallization in a form of misoriented columnar crystals of various degrees of roughness and length radially located with a slight turn about the axis (Fig. 1, c).

The results obtained in hot twisting tests of continuously cast billets are presented in Figs. 2–4 by curves of dependence of average twist number values and twisting forces on the test temperature and indicate influence of macrocrystalline structure of the continuously cast metal on distribution of plastic and force characteristics in the section of the billets under study.

The following regularity can be traced in distribution of plastic properties over the billet section for the CCB metal with a developed transcrystallization zone, regardless of the steel grade (10U steel grade or ‘20’ boiler steel grade) and diameter (210 mm or 150 mm). The number of twists before fracture of the specimens cut from the intermediate zone at all temperatures studied was less than the corresponding figures for the specimens cut from the axial zone. Moreover, there was a sharp increase (~40%) in the number of the specimen twists before failure for the intermediate zone beginning from 1200 °C. The curves of dependence of the twist number on temperature for the specimens cut from different cross section zones of these billets (axial and intermediate) had a similar form with a pronounced maximum at 1225–1230 °C. A tendency to a decrease in the deformation (twisting) force in the studied temperature range was observed for the metal of axial and intermediate zones of the mentioned CCMs while values of the deformation force differed insignificantly in the temperature range of 1150–1250 °C for the metal of the same zones. The smallest value of the deformation force was obtained both for the axial and intermediate zones at a test temperature of 1250 °C. For the studied CCBs characterized by presence of a developed zone of columnar crystals in the metal macrostructure, heating before piercing is recommended to be carried out in the tube processing to a temperature of 1200–1250 °C.

When testing for hot twisting of specimens of the CCBs made of 20U steel grade which have a macrocrystalline structure different from the above-mentioned billets, a lower level of force and plastic characteristics and a fundamentally different regularity of their distribution over the billet cross-section were obtained. The curves of dependence of the number of twists on temperature for the specimens taken from different zones of the billet cross-section have different forms. This curve has a pronounced maximum corresponding to temperature of 1220 °C for the axial zone. For the intermediate zone, the number of specimen twists sharply increases up to the specimen failure beginning from this temperature to the limiting test temperature (1250 °C). The curve of dependence of the number of twists on temperature is of incomplete nature. Deformation forces for the specimens taken from the axial zone of a CCM made of 20U steel grade practically are higher than those for the specimens taken from the intermediate zone in the entire temperature range under study with an exception of the temperature of 1200 °C at which values of this indicator are...
Conclusions

1. Influence of the macrocrystalline structure on processing plasticity of metal of nonworked continuously cast billets made of carbon steel grades was confirmed. A difference in behavior of various zones in the CCB cross section in the course of hot twisting tests was established.

2. Optimal temperature interval of heating before piercing (in the process of tube processing) the continuously cast billets made of carbon steel grades having the metal macrostructure characterized by presence of a developed zone of columnar crystals relatively evenly distributed over the billets cross section has been determined.

3. It was shown that it is necessary to continue studies of the processing plasticity of metal of the continuously cast billets having different macrocrystalline structures in order to minimize formation of defects in tubes production.

the same for different metal zones. The smallest value of the deformation force was observed at test temperature of 1225 °C for the axial zone and at 1200 °C for the intermediate zone. Besides, against the background of the general tendency of decrease in the deformation force with an increase in test temperature, an anomalous increase in the deformation force was observed at 1175 °C for the specimens cut from both axial and intermediate zones. Such ambiguous results obtained in the twist tests of the specimens taken from the CCMs made of 20U steel grade are explained by peculiarities of the steel structure state as well as by the place of taking specimens that necessitates further studies. Moreover, taking into account the incomplete character of the curve of dependence of the number of twists of the specimens from the intermediate zone on temperature when conducting studies of the processing plasticity of the CCB metal, it is necessary to raise maximum of the twisting test temperature up to 1300 °C.

1. Потапов И.Н., Коликов А.П., Данченко В.Н. и др. Технология производства труб. М.: Металлургия, 1994. 528 с.
2. Шевакин Ю.Ф. Технология производства труб. М.: Интермет Инжиниринг, 2005. 496 с.
3. Осадчий В.Я., Вавилин А.С., Зимовец В.Г. Технология и оборудование трубного производства. М.: Интермет Инжиниринг, 2001. 608 с.
4. Чикалов С.Г. Производство бессовочных труб из непрерывнолитой заготовки. Волгоград: Комитет по печати и информ. 1999. 416 с.
5. Голубчик Р.М., Меркулов Д.В. Режимы прошивки заготовок. Теория и практика металлургии. 2006. № 6. С. 105–111.
6. Черных И.Н., Струнин Д.О., Шкуратов Е.А. Определение технологических факторов прокатки, способствующих возникновению дефектов поверхности на трубах. Вестник ЮРГУ. Серия «Металлургия». 2018. Т. 18. № 3. С. 51–59.
7. Гуляев Г.И., Правосудович В.В., Кашкашиев Г.В. Атлас дефектов стальных горячекатаных бессовсенных труб. Тбилиси: Сакартвели, 1991. 152 с.
8. Правосудович В.В., Сокуренко В.П., Данченко В.Н. и др. Дефекты стальных слитков и проката. М.: Интермет Инжиниринг, 2006. 384 с.
9. Мочалов Н.А., Галкин А.М., Мочалов С.Н., Парфенов Д.Ю. Пластометрические исследования металлов. М.: Интермет Инжиниринг, 2003. 318 с.
10. Голубчик Р.М. Определение системы использования ресурса пластических свойств при горячей обработке давлением. Металлы. 1998. № 6. С. 44–47.
11. Темлянцев М.В., Старикин В.С., Семахин В.В. и др. Анализ особенностей температурных режимов нагрева непрерывнолитых и катаных стальных заготовок. Известия вузов. Черная металлургия. 2004. № 10. С. 46–47.
12. Минаев А.А., Захур М., Коновалов Ю.В. Специфика использования катаной и непрерывнолитой заготовки для производства труб. Производство проката. 2005. № 4. С. 29–37.
13. Темлянцев М.В., Старикин В.С., Копотов Е.А. и др. Рациональный выбор режима нагрева стальных слябов под прокатку. Известия вузов. Черная металлургия. 2001. № 2. С. 55–58.
14. Журавлев Б.К., Лоскутов Д.Р., Громов В.Е. Пластичность малолегированных и нержавеющих марок стали. Известия вузов. Черная металлургия. 1997. № 6. С. 51–54.
15. Опрышко Л.В., Головняк Т.В. Качество металла котельной трубной заготовки производства ПАО «Днепровский металлургический комбинат». Метал та лиття України. 2019. № 10–12. C. 47–55. DOI: https://doi.org/10.15407/steelcast2019.10.047
16. Попандопуло И.К., Михневич Ю.Ф. Непрерывная разливка стали. М.: Металлургия, 1990. 296 с.
17. Опрышко Л.В. Макроструктура непрерывнолитых заготовок для производства котельных труб. Метал та лиття України. 2012. № 5. С. 15–19.
18. Смирнов А.Н., Пилищенко В.Л., Минаев А.А. и др. Процессы непрерывной разливки. Монография. Донецк: ДонНТУ, 2002. 536 с.
REFERENCES

1. Potapov, I.N., Kolikov, A.P., Danchenko, V.N. et al. (1994). Pipe production technology. Moscow: Metallurgiya, 528 p. [in Russian].

2. Shevakin, Yu.F. (2005). Plastic metal working. Moscow: Internet Engineering, 496 p. [in Russian].

3. Osadchii, V.Ya., Vavilin, A.S., Zimovets, V.G. (2001). Pipe production technology and equipment. Moscow: Internet Engineering, 608 p. [in Russian].

4. Chikalov, S.G. (1999). Production of seamless pipes from continuous cast billets. Volgograd: Press Committee, 416 p. [in Russian].

5. Golubchik, R.M., Merkulov, D.V. (2006). Piece piercing modes. Teoriya i praktika metallurgii. Theory and practice of metallurgy, no. 6, pp. 105–111 [in Russian].

6. Chernykh, I.N., Struin, D.O., Shkuratov, E.A. (2018). Determination of technological factors of rolling ability to occurrence of surface defects on pipes. Vestnik YuUrGU. Seriya "Metalurgiya". Bulletin of the South Ural State University. Ser. "Metalurgy", vol. 18, no. 3, pp. 51–59 [in Russian].

7. Gulyaev, G.I., Pravosudovich, V.V., Kashakashvili, G.V. (1991). Defects atlas of hot-rolled steel seamless pipes. Tbilisi: Sakartvelo, 152 p. [in Georgian].

8. Pravosudovich, V.V., Sokurenko, V.P., Danchenko, V.N. et al. (2006). Defects of steel ingots and rolled products. Moscow: Internet Engineering, 384 p. [in Russian].

9. Mochalov, N.A., Galkin, A.M., Mochalov, S.N., Parfenov, D.Yu. (2003). Plastometric studies of metal. Moscow: Internet Engineering, 318 p. [in Russian].

10. Golubchik, R.M. (1998). Determination of the system of using the resource of plastic properties during hot forming. Metally. Metals, no. 6, pp. 44–47 [in Russian].

11. Temlyantsev, M.V., Starikov, V.S., Semahin, V.V. et al. (2004). Analyses of peculiarities of temperature regimes of heating of continuously cast and rolled steel billets. Izvestiya vuzov. Chernaya metallurgiya. Proceeding of universities. Ferrous metallurgy, no. 10, pp. 46–47 [in Russian].

12. Minaev, A.A., Zakhr, M., Konovalov, Yu.V. (2005). Specificity of using rolled and continuous casting for pipe production. Proizvodstvo prokata. Production of rolled metal, no. 4, pp. 29–37 [in Russian].

13. Temlyantsev, M.V., Starikov, V.S., Kolotov, E.A. et al. (2001). Rational choice of heating mode for steel slabs for rolling. Izvestiya vuzov. Chernaya metallurgiya. Proceeding of universities. Ferrous metallurgy, no. 2, pp. 55–58 [in Russian].

14. Zhuravlev, B.K., Losrutov, D.R., Gromov, V.E. (1997). Plasticity of low-alloy and stainless steel grades. Izvestiya vuzov. Chernaya metallurgiya. Proceeding of universities. Ferrous metallurgy, no. 6, pp. 51–54 [in Russian].

15. Opryshko, I.V., Golovnyak, T.V. (2019). Quality of metal of the boiler tube billets manufactured by PJSC “Dneprovsky Iron & Steel Integrated Work”. Metal and Casting of Ukraine, no. 10–12, pp. 47–55, doi: https://doi.org/10.15407/steelcast2019.10.047 [in Russian].

16. Popandopulo, I.K., Mikhnevich, Yu.F. (1990). Continuous casting of steel. Moscow: Metallyrgiya, 296 p. [in Russian].

17. Opryshko, L.V (2012). Macrostructure in the continuously cast billets used in making of boiler tubes. Metal and Casting of Ukraine, no. 5, pp. 15–19 [in Russian].

18. Smirnov, A.N., Pilyushenko, V.L., Minaev, A.A. et al. (2002). Processes of continuous casting of steel. Monograph. Donetsk: DonNTU, 536 p. [in Russian].

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Анотація
Л.В. Опришко, зав. відділенням «Матеріалознавства, експертизи та технології виробництва труб та виробів з чорних і кольорових металів та сплавів», зав. лабораторією «Матеріалознавства та технології виробництва труб та виробів для теплової і атомної енергетики», e-mail: liudmila.oprayshko@gmail.com, https://orcid.org/0000-0002-5444-311X
Т.В. Головняк, зав. сектору «Експертних досліджень металопродукції з чорних і кольорових металів та сплавів», e-mail: tatyana.golovniak@gmail.com, https://orcid.org/0000-0002-8853-7034
Державне підприємство «Науково-дослідний та конструкторсько-технологічний інститут трубної промисловості ім. Я.Ю. Осади» (ДП «НДТІ»), Дніпро, Україна

Технологічна пластичність металу недеформованих безперервнолитих трубних заготовок
В статті наведено результати досліджень технологічної пластичності (здібності до гарячого деформування) металу недеформованих безперервнолитих трубних заготовок (БЛЗ) з вуглецевих марок сталі виробництва ВАТ «МЗ «ДНІ-ПРОСТАЛЬ». Технологічну пластичність безперервнолитих заготовок дослідували шляхом проведення випробувань на гаряче скручування в інтервалі температур від 1100 до 1250 °C на обладнані ДП «НДТІ». Випробування на гаряче скручування піддавали БЛЗ, які мають різну макрокристалічну будову. Визначено температурні інтервали максимальної пластичності металу з вуглецевих марок сталі. Досліджено розподіл показників випробувань на гаряче скручування (число скручувань до руйнування та зусилля скручування) по перетину БЛЗ. Виявлено вплив макрокристалічної будови на поведінку металу БЛЗ в процесі випробувань на гаряче скручування.
Результати досліджень мають важливе наукове та практичне значення в умовах все більш широкого застосування БЛЗ для виробництва труб різного призначення. Вперше отримано результати досліджень технологічної пластичності металу недеформованих безперервнолитих заготовок з вуглецевих марок сталі з різною макрокристалічної будовою, які дозволяють рекомендувати оптимальні температурні нагріву вихідних БЛЗ перед гарячою прокаткою. Нагрів безперервнолитих заготовок за оптимальних температур, з розрахунком їх фактичної макрокристалічної будови, дозволить збільшити пластичність і зменшити спротив деформуванню металу цих заготовок в процесі прошивки і мінімізувати утворення дефектів поверхні труб, які виготовлені з БЛЗ.
Результати досліджень також послужать підставою для удосконалення технології виготовлення БЛЗ на ВАТ «МЗ «ДНІ-ПРОСТАЛЬ» з метою отримання макрокристалічної будови металу заготовок, яка забезпечить задовільний рівень технологічної пластичності, а також — більш рівномірний розподіл пластичних властивостей по перетину БЛЗ.

Ключові слова
Недеформована безперервнолита трубна заготовка, макрокристалічна будова, стовпчасті кристали, рівноосні розорієнтовані кристали, технологічна пластичність, випробування на гаряче скручування, кількість скручувань до руйнування, зусилля скручування.