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Ivanov A. Chief specialist in the production planning of finished products, PJSC "Dniprospetstal", Zaporizhzhia, Ukraine, *e-mail: ivanovandrei@dss.com.ua*

Matiukhin A. Candidate of Technical Sciences, Associate Professor, Head of the Department of Metal Forming of National University "Zaporizhzhia Polytechnic", Zaporizhzhia, Ukraine, *e-mail: matiukhin85@gmail.com*, ORCID: 0000-0002-2261-0577

Ben A. Senior Lecturer of the Department of Metal Forming of National University "Zaporizhzhia Polytechnic", Zaporizhzhia, Ukraine, *e-mail: benanna1985@gmail.com,* ORCID: 0000-0002-9765-8030

Kryvykh Yu. Senior Lecturer of the Department of Aviation Engine Technology of National University "Zaporizhzhia Polytechnic" , Zaporizhzhia, Ukraine, *e-mail: juliya.krivikh@gmail.com*, ORCID: 0000-0002-3183-8776

Kulabnieva O. Senior Lecturer of the Department of "Foreign Philology and Translation" of National University "Zaporizhzhia Polytechnic", Zaporizhzhia, Ukraine, *e-mail: kulabneva.elena@gmail.com*, ORCID: 0000-0003-3894-3891

DETERMINATION OF THE STRESSED METAL STATE DURING HOT ROLLING BY THE FINITE ELEMENT METHOD

Purpose. *Determination of the stress-strain state of the metal during the rolling of large ingots to prevent the occurrence of internal defects, and determining the effect of forced cooling of the ingot surface during hot rolling on the stress-strain state.*

Research methods. *Finite element method, upper estimate method.*

Results. *Based on the finite element method, a comparative simulation of the stress-strain state of the ingot with different cooling times was performed. As a result of the study, it was established that the forced cooling of the ingot surface during hot rolling helps to reduce the probability of the internal continuity defect forming. The given results of comparison of the distribution of strain intensity along the rolling cross-section in the basic version and with additional annealing indicate a decrease in the probability of formation of discontinuities in the axial zone of the ingot. This, in turn, proves the effectiveness of forced annealing of the surface layers of the ingot (workpiece).*

Scientific novelty. *A mathematical model of the distribution of the main stress state components was developed. It took into account the redistribution of temperatures and, as a result, the mechanical properties of the metal according to the height of the deformation focus during the hot rolling of relatively large blanks.*

Practical value. *The use of forced cooling leads to a significant increase in hydrostatic and normal stresses in the axial zone, reducing the probability of the formation and subsequent growth of internal continuity defects. Thus, the quality of finished products increases, in particular, valuable rolled products made of special grades of steel.*

Key words: *hot rolling, cooling of surface layers, redistribution of temperatures and stresses, ingot, stressed state, mathematical modeling, finite element method.*

Introduction

During the rolling of relatively thick strips characterized by the ratio of the length of the plastic deformation zone Lpl to the average thickness of the strip hcp in the range Lpl/hcp=0.5...2.0, significant tensile stresses act in the axial zone. At the same time, macro inhomogeneities associated with the crystallization features of a continuously cast billet or ingot are observed in the above zone. The listed factors adversely affect the quality of finished rolled metal.

Analysis of research and publications

There are various methods of intensification of plastic deformation in the axial layers of the rolled strip [1–3]. The most common methods include: increasing the diameters of rolls, increasing single crimps, increasing the total deformation, etc. [4–5]. These methods require significant modernization of equipment and, therefore, significant capital investments. There are also technological methods that increase the quality of the rolled product, for example, cooling the surface layers of the metal before its deformation, which leads to a decrease in the plasticity of the contact layers, while maintaining the plasticity in the axial zone of the rolled strip, and, therefore, to a significant change in the stress-strain state [6–9]. To determine the effectiveness of the described method, a qualitative and quantitative assessment of the stress-strain state of the rolled metal is required under a non-uniform temperature field [10–13].

The purpose of the work

The purpose of the study is to determine the effect of forced cooling of the ingot surface during hot flattening on the stress-strain state and closure of axial defects using a software product based on the finite element method – DeForm 3D.

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Research material and methodology

A 4300 kg ingot made of steel 45 (AISI-1045) used at PrJSC Dniprospetsstal was chosen to simulate the rolling process. According to the passport, the axial porosity of the ingot has a length of ≈1000 mm and a width of ≈ ≈ 60 mm. Figure 1 shows a ¼ part of an ingot with a cavity of the above dimensions. Rolling of ingots was carried out on the procurement cage according to the scheme presented in Table 1. The sketch of gauges is presented in Figure 2.

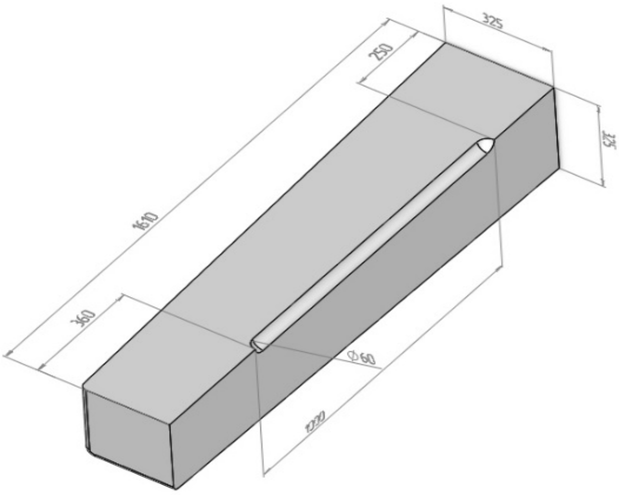

Figure 1. ¼ part of the ingot with a cavity of Ø60 mm, weighing 4300 kg

To determine the effect of forced cooling of the surface layers of the ingot on the stress-strain state, the process of rolling on a crimping cage with different pauses before loading the metal into the first gauge was considered. At the same time, the conditions of the rolling process (friction conditions, roll rotation speed, roll diameter, etc.) and the rheological properties of the metal remained unchanged. For the basic version, a cooling time equal to 45 s was chosen, which corresponds to the average time of moving the ingot from the area of the heating wells to the mold cage. For the second option, the additional cooling time was 600 s, thus, the total time was 645 s.

For the basic version, the temperature of the ingot surface is ≈ 1060 °C, the temperature of the axial layers is ≈ 1150 °C (Fig. 3a). In case of additional cooling, the surface temperature of the ingot is ≈ 895 °C, the temperature of the axial layers is ≈ 1150 °C, at the same time it is necessary to note the presence of a zone ≈ 50–60 mm thick with a temperature of ≈ 1090 °C (Fig. 3b).

After deformation, the temperature field changed as follows (Fig. 4): in the basic version, the temperature of the contact layers is ≈ 1180 °C, the temperature of the axial zone is ≈ 1230 °C, with additional cooling, the temperature of the cooled layers is ≈ 1130 °C, the temperature of the axial zone is ≈ 1220 °C.

Table 1 – Rolling scheme ≠260×235 mm from ingot weighing 4300 kg grade 45

Caliber	Passage number	Compression Δh, mm	Extension Δb, mm	Height H, mm	Width B, mm
				650	650
	1	75	5	575	655
	2	75	5	500	660
	canting				
I	3	85	10	575	510
	4	85	10	490	520
	5	85	10	405	530
	6	85	10	320	540
	canting				
	7	110	20	430	340
	8	110	20	320	360
II	canting				
	9	70	15	290	335
	10	70	15	220	350
	canting				
III	11	90	15	260	235

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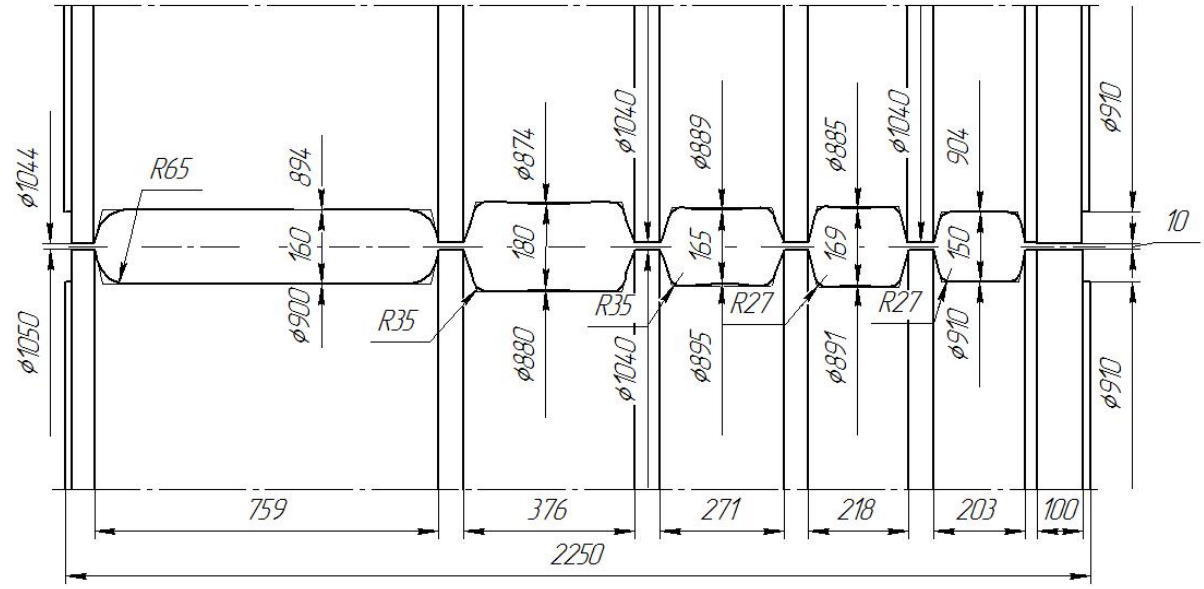
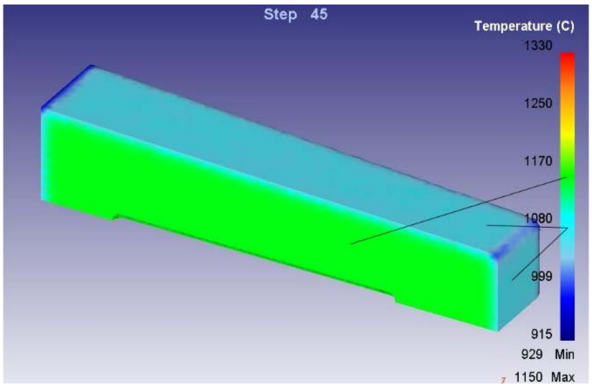
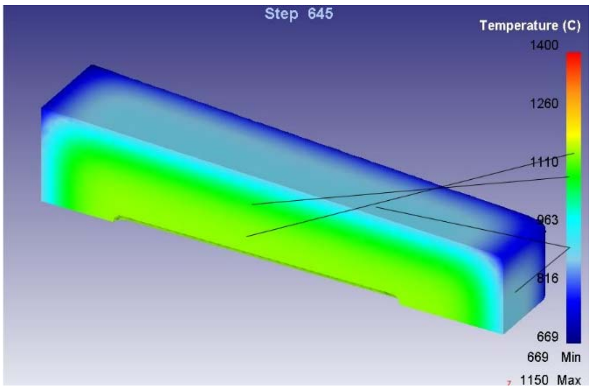


Figure 2. Calibrating the rolls of the crimping cage



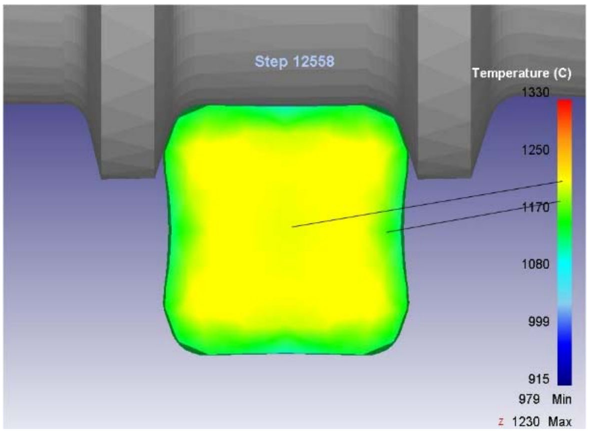
a



b

Figure 3. Temperature distribution across the rolling section before deformation:
a – basic version, b – with additional cooling

It should be noted that the thickness of the cooled layers is 65 mm, which is almost twice the thickness (S = 35 mm) of the pro-contact layers in the basic version. The temperature difference of the axial zone in the considered variants is only 10 °C, the temperature of the surface layers differs more significantly, by 50 °C, the temperature gradient along the rolling section in the basic variant is Δt = 50 °C, in the alternative variant it is almost twice as large Δt = 90 °C.



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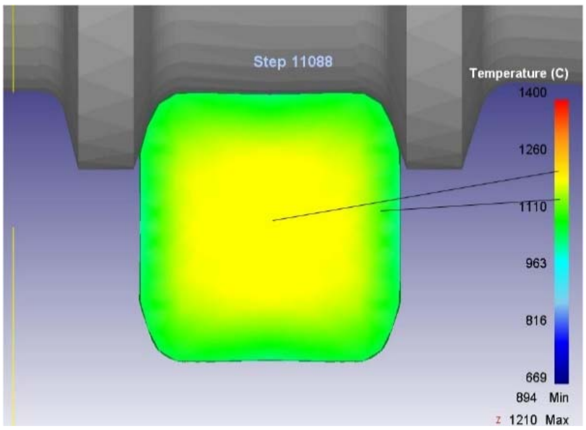

b

Figure 4.Temperature distribution along the rolling section after deformation:
(a – basic version, b – with additional cooling)

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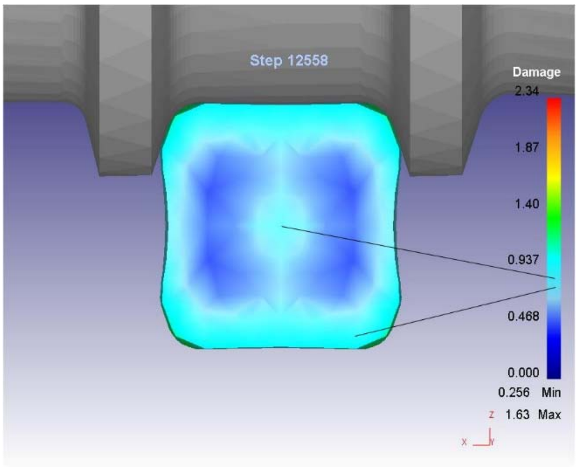
Research results

The data obtained as a result of modeling indicate that the degree of use of the plasticity margin, according to the Cockcroft-Letham criterion, is 28 % lower in the axial zone and 17 % lower on the surface (Fig. 5), compared to the basic version [14–16]. The distribution of the intensity of deformations can be compared for the basic and the investigated variant of rolling (Fig. 6). At the same time, in the studied variant, the intensity of deformation is higher in the zones adjacent to the faces of the ingot, which are cooled more intensively compared to the plane.



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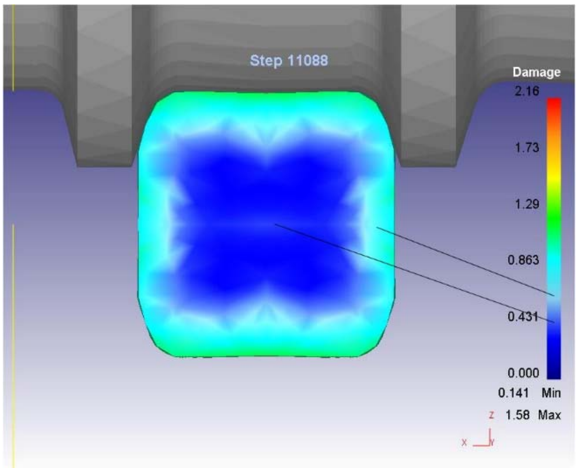
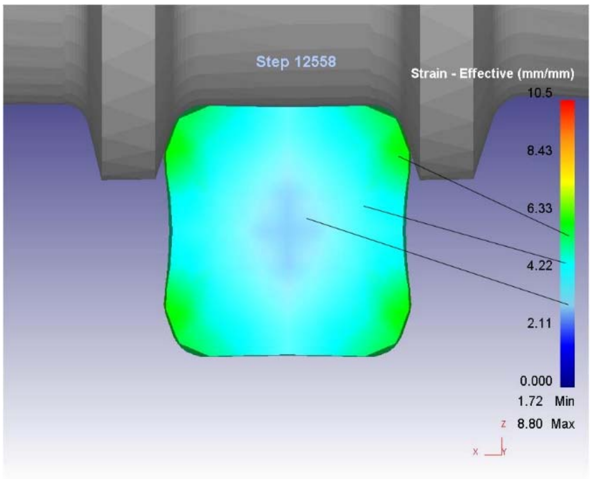


b

Figure 5. Distribution of the degree of use of the plasticity reserve by the rolling section:
a – basic version, b – with additional cooling

The size of the hole simulating the axial porosity of the ingot in the basic version after the eleventh pass was 5.34x0.83 mm, in the tested version the hole is welded after the eighth pass.



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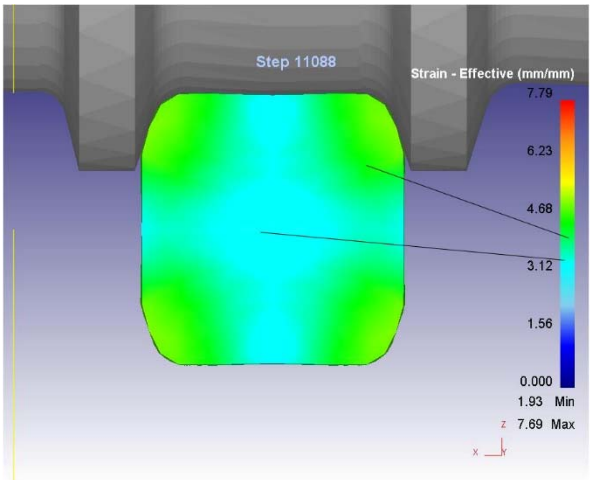

b

Figure 6. Distribution of the intensity of deformations by the rolling section:
a – basic version, b – with additional cooling

Discussion

The given results of the comparison indicate a decrease in the probability of formation of discontinuities in the axial zone of the ingot, which, in turn, proves the effectiveness of forced cooling of the surface layers of the ingot (workpiece). At the same time, it should be taken into account that the cooling leads to an increase in the rolling force, so for the basic version, the maximum rolling force was 9.27 MN, and for the tested one – 15.2 MN.

Conclusions

Using the finite element method (DeForm 3D), a comparative simulation of the stress-strain state of the ingot was performed with different cooling times – 45 s and 645 s. As a result of the study, it was established that the forced cooling of the ingot surface during hot rolling helps to reduce the probability of the formation of internal continuity defects.

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ВИЗНАЧЕННЯ НАПРУЖЕНОГО СТАНУ МЕТАЛУ ПРИ ГАРЯЧОМУ ПРОКАТУВАННІ МЕТОДОМ СКІНЧЕННИХ ЕЛЕМЕНТІВ

Іванов А. В. — головний спеціаліст з планування виробництва готової продукції ПрАТ «Дніпроспецсталь», м. Запоріжжя, Україна, *e-mail:ivanovandrei@dss.com.ua*

Матюхін А. Ю. — канд. техн. наук, доцент, завідувач кафедри «Обробки металів тиском» Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail:matiukhin85@gmail.com*, ORCID: 0000-0002-2261-0577

Бень А. М. — старший викладач кафедри «Обробки металів тиском» Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: benanna1985@gmail.com*, ORCID: 0000-0002-9765-8030

Кривих Ю. І. — старший викладач кафедри «Технології авіаційних двигунів» Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail:juliya.krivikh@gmail.com*, ORCID: 0000-0002-3183-8776

Кулабнєва О. А. — викладач кафедри «Іноземна філологія та переклад» Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: kulabneva.elena@gmail.com*, ORCID:0000-0003-3894-3891

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Мета роботи. *Визначення напружено-деформованого стану металу при прокатуванні крупних злитків для запобіганню виникненню внутрішніх дефектів та визначення впливу примусового підстужування поверхні злитка під час гарячого прокатування на напружено-деформований стан.*

Методи дослідження. *Метод скінченних елементів, метод верхньої оцінки.*

Отримані результати. *На основі методу скінченних елементів виконано порівняльне моделювання напружено-деформованого стану злитка з різним часом підстужування. У результаті дослідження встановлено, що примусове підстужування поверхні злитка під час гарячого прокатування сприяє зниженню ймовірності утворення внутрішніх дефектів суцільності. Наведені результати порівняння розподілу інтенсивності деформацій за перерізом розкату за базовим варіантом та з додатковим підстужуванням, свідчать про зниження ймовірності утворень несуцільностей в осьовій зоні злитка, що, своєю чергою, доводить ефективність примусового підстужування поверхневих шарів злитка (заготовки).*

Наукова новизна. *Розроблено математичну модель розподілів основних компонентів напруженого стану з урахуванням перерозподілу температур і, як наслідок, механічних властивостей металу за висотою вогнища деформації під час гарячого прокатування відносно великих заготовок.*

Практична цінність. *Застосування примусового підстужування зумовлює істотне підвищення гідростатичних і нормальних напружень в осьовій зоні, що, своєю чергою, знижує ймовірність утворення і подальшого зростання внутрішніх дефектів суцільності. Таким чином, підвищується якість готової продукції, зокрема вартісних прокатних виробів з спеціальних марок сталей.*

Ключові слова: *гаряче прокатування, підстужування поверхневих шарів, перерозподіл температур і напружень, злиток, напружений стан, математичне моделювання, метод скінченних елементів.*

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